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**The Supersonic Hydrogen-Fluorine Combustion Facility**

**Design Review Report**

**Version 4.0**

by  
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**GALCIT Internal Report**

**30 August 1989**

## Acknowledgements

This development of the facility to be described below is the outgrowth of a design, theoretical and experimental effort at GALCIT that began over ten years ago to study high Reynolds number turbulent mixing under Air Force Office of Scientific Research sponsorship. A large number of people have contributed to the development of this facility, which has been realized as a result of their contributions and the long-term support by AFOSR, with Dr. Julian Tishkoff the current program manager, which we gratefully acknowledge\*.

The first phase of that effort, which involved the study and behavior of subsonic shear layers, was realized in the subsonic shear layer facility which was designed and fabricated with the aid and contributions of several people. That design was modeled after the smaller subsonic facility built by Wallace (1981) under the supervision of

- Garry Brown, Professor in Aeronautics at the time and presently director of ARL in Australia.

The GALCIT subsonic facility design was begun by

- Brian Cantwell, Research Fellow in Aeronautics at the time, presently Professor at Stanford,

in collaboration with and under the guidance of Garry Brown. It was completed and used as part of the Ph.D. thesis research of

- M. Godfrey Mungal, Graduate Research Assistant and subsequently Research Fellow in Aeronautics, presently Assistant Professor at Stanford,

under the guidance of

- H. W. Liepmann, Director of GALCIT at the time and presently Professor Emeritus in Aeronautics,

and

- P. E. Dimotakis, Professor of Aeronautics & Applied Physics,

with contributions by

- C. E. Frieler, Graduate Research Assistant in Aeronautics.

The subsonic facility was fabricated largely on campus at

- Central Engineering Services, with considerable design assistance by Mr. Norm Keidel (manager).

Small components were fabricated in the

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- Aeronautics Machine Shop, under the supervision of Mr. George Lundgren.

The facility was assembled and tested by M. G. Mungal aided by

- E. Dahl, GALCIT Technical staff, who has also been largely responsible for the subsonic facility operations over its life-span,
- C. Hemphill, GALCIT Technical Staff (electrical installations),

and

- D. Lang, Staff Engineer, who has made numerous contributions over the years to associated instrumentation, electronics and data acquisition systems that have made many of the experiments possible and extended the operating envelope of both the subsonic facility and the supersonic facility to be described below beyond what would otherwise have been feasible.

Preliminary design studies of a supersonic shear layer facility were begun in parallel, with an eye towards addressing Mach number issues in turbulent mixing and combustion. These were undertaken under the guidance of H. W. Liepmann and Garry Brown, with contributions by M. G. Mungal,

- J. C. Hermanson, as part of his Ph.D. research effort at the time, presently at UTRC,

the Central Engineering Services, and C. E. Frieler.

The final design and fabrication of the supersonic shear layer facility was begun as part of the Ph.D. research effort of

- J. Hall, Graduate Research Assistant in Aeronautics.

with a large number of Caltech people contributing to the design and construction. Specifically,

- personnel at Caltech's Central Engineering Services:

- Norm Kiedel, manager CES,
- Lou Johnson, assistant manager,
- George Yamamoto, designer,
- Ralph Ortega, welder,

and machinists

- Rick Paniagua, Mike Gerfen, Steve Siguenza, Betty Swartout and Bovan Bang (main pressure regulator, test section, shower tunnel, instrument rake and a host of minor items),

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- Rick Gilbrech, Graduate Research Assistant in Aeronautics (materials testing, gas delivery system).
- Dimitri Papamoschou, Research Fellow in Aeronautics. Currently, Assistant Professor, UC Irvine (main pressure regulator, test section).
- Don Coles, Professor in Aeronautics (High Pressure Tank injector system),
- Henning Rosemann, Research Fellow in Aeronautics (Regulator control software and testing).
- Dan Lang, Staff Engineer (Data acquisition system, regulator control system).
- Earl Dahl, GASCIT technical staff (assorted design ideas plus assembly and installation of everything).
- Cliff Frieler, Graduate Research Assistant (design suggestions and problem solving help on just about everything).

## 1. Introduction

The Supersonic Hydrogen-Fluorine Combustion Facility is being constructed for the purpose of conducting supersonic turbulent mixing and combustion experiments in two-dimensional shear layers. This facility is designed to operate in a blowdown mode, with a nominal 3 sec run time\*\*.

The high speed stream will nominally carry mixtures of  $H_2$  and  $NO$ , in selected diluents, at supersonic velocities. The other stream will carry  $F_2$ , in selected diluents, at subsonic velocities. The resultant  $H_2/F_2/NO$  chemical system will react within the turbulent mixing layer at roughly atmospheric pressure. It is anticipated that the facility will be able to operate in the fast chemistry regime for sufficiently high reactant concentrations. The relevant analysis was documented by Dimotakis & Hall (1987). Very high shear layer Reynolds numbers will be attainable, *i.e.*

$$Re_\delta \equiv \frac{\Delta U \delta}{\nu} \approx 6 \times 10^6, \quad (1a)$$

where

$$\Delta U \equiv U_1 - U_2 \quad (1b)$$

is the free stream velocity difference across the shear layer,

$$\delta = \delta(x) \quad (1c)$$

is the local shear layer transverse extent, and  $\nu$  is an appropriate measure of the kinematic viscosity. A list of projected performance specifications is presented in Table 1, based on the sample calculations shown in Appendix F. The facility floor plan is shown in Fig. 1 and the overall plumbing schematic is shown in Fig. 2.

This version (4.0) of the report is intended to provide a general overview of the facility and its capabilities. It includes brief descriptions of all major components, including those elements of the fluorine gas delivery system that were ignored in the previous versions. More detailed information on the facility can be found in the appendices, including engineering drawings, device data sheets and sample calculations.

At the time of this writing, the construction of the facility has been completed and component testing has begun. Hence, this report describes the facility in essentially its final form.

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\*\* Slightly longer run times are possible at the lower Mach numbers.

## 2. Background information

This new facility is built on the site of the subsonic  $HF$  reacting shear layer laboratory at Caltech. See Ph.D. theses by Mungal (1983) and Hermanson (1985) for available documentation. Some of the components of the subsonic facility were incorporated into the new one:

- o the low speed stream (fluorine) gas delivery network,
- o the Schlieren optical system

and

- o various minor structural and plumbing elements.

The major portion of the supersonic facility, however, has been designed and built from scratch, with inputs from the previous preliminary design efforts. Both the subsonic and the supersonic parts of the new facility will be described in this report.

Three major design drivers served to define the basic configuration of the facility. The first was the desire to incorporate as much of the old facility as possible into the new one. The second was the need to generate convective Mach numbers in excess of roughly 1.4, which we predicted would capture most of the relevant physics of the flow<sup>†</sup>. The third design driver was that of producing a reacting flow characterized by sufficiently fast chemical kinetics so as to be a mixing-limited flow, permitting the use of the products, or heat release, of chemically reacting runs to be used as a quantitative measure of the amount of molecular mixing.

Of those three design drivers, the issue of chemical kinetics proved to be the most important one. It dictated the selection of  $H_2/F_2/NO$  chemistry; no other chemical system, to our knowledge, can produce fast chemistry results in the supersonic flow regime of interest in a laboratory scale facility. The kinetics problem also forced us to operate the test section at atmospheric pressure so as to keep the molecular number density high enough. The selection of this pressure rippled through the entire design, dictating the high supply pressures (100 atm) needed for the highest Mach number flows. Finally, kinetics considerations suggested the desirability of having an optionally higher than ambient stagnation temperature for the supersonic flow. This high temperature specification also rippled through the design and required the use of piping and valves compatible with high temperature gas flows.

Two factors contributed to the decision to make this facility bisonic, that is, with one stream supersonic and one stream subsonic. First, the results of Papamoschou &

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<sup>†</sup> The facility design actually implemented should permit convective Mach numbers up to, roughly, 2. See the discussion in Dimotakis (1989).

Roshko (1986), Papamoschou (1986) and Papamoschou & Roshko (1988) suggested that the convective Mach number  $M_c$  was the physically important scaling parameter. Note that there are actually two convective Mach numbers defined by

$$M_{c1} = \frac{U_1 - U_c}{a_1} \quad \text{and} \quad M_{c2} = \frac{U_c - U_2}{a_2}$$

where  $U_1$  and  $U_2$  are the free stream velocities,  $a_1$  and  $a_2$  are the speeds of sound and  $U_c$  is the convective velocity of the large scale structures. The second factor was a serious safety concern with respect to supersonic flows of fluorine gas in the laboratory. The choice of a bisonic design, with supersonic hydrogen and subsonic fluorine, served to alleviate most of the safety concerns while at the same time did not compromise our ability to investigate supersonic shear layers since we could more easily generate convective Mach numbers greater than unity with one gas stream subsonic. We should note, however, that should that become an issue, the pressure capability of the fluorine gas supply part of the facility is such as to also allow a supersonic low speed stream, albeit at modest Mach numbers.

### 3. Low speed fluorine gas delivery network

We were able to utilize virtually all the components of the fluorine gas delivery network from the subsonic facility. Although this hardware has been documented previously (Mungal 1983 and Hermanson 1985), a brief overview of its components and operation will be presented below.

The fluorine gas delivery is accomplished with a blowdown technique. There are six key elements:

1. the source gas tank farm,
2. the mixing vessel,
3. the reactant tank,
4. the surge tank,
5. the fast-acting valve,

and

6. the flow metering valve.

See Fig. 2. The basic operation is as follows:

The fluorine and inert gases are first loaded into the mixing vessel. Partial pressure measurements are used to set the concentrations of the constituent gases. These gases are then transferred to a Teflon bag which is located inside the reactant tank. This Teflon bag acts as a bladder bag and is squeezed at run time by nitrogen gas from the surge tank. The surge tank, in essence, acts as a constant pressure source, while the Teflon bag acts like a massless piston. The fast-acting valve and the metering valve provide the shut-off and flow metering functions between the reactant tank and the test section. Acoustic dampening is provided by a high porosity screen stack at the exit of the metering valve.

A summary of the performance specifications for the low speed fluorine gas delivery network is presented in Table 1.

#### 4. High speed $H_2/NO$ gas delivery network

The  $H_2/NO$  gas delivery network is also based on a blowdown technique. Owing to the high mass fluxes, however, it was not practical to provide a large enough tank to serve as a constant pressure source, as was done with the surge tank in the fluorine gas delivery network. This necessitated a pressure regulating device which would compensate for the falling pressure in the reactant tank during a run.

The high speed gas delivery system network is comprised of four major elements:

1. The source gas tank farm.
2. The  $H_2/NO$  Reactant Tank.
3. The main shut-off valve.
4. The main pressure regulator.

A four-inch stainless steel pipe delivers the gas from the  $H_2/NO$  Reactant Tank to the test section via the shut-off valve and the regulator. Acoustic dampening is provided by a six-foot long pipe lining downstream of the pressure regulator. This lining is essentially a silencer, consisting of an annulus of aluminum screen sandwiched between the pipe wall and a cylindrical perforated plate.

The four major elements will be described separately below.



#### 4.1 High pressure source gas tank farm

Figure 2 shows that there are five separate sources of gas for the high speed leg of the facility. Hydrogen is supplied from a three bottle manifold. Nitric oxide is supplied from a single bottle. High pressure nitrogen, helium and argon are supplied from manifolds at 2500 *psi* and 6000 *psi*. Finally, a dewar of liquid nitrogen is also available, needed to supply large volumes of high purity, low pressure gas for purging operations.

#### 4.2 The H<sub>2</sub>/NO reactant tank

This tank can be divided into four major components:

- a. The tank itself.
- b. The internal packing.
- c. The external heaters and insulation.
- d. The injector.

A drawing of the tank, the internal packing and the support skirt is included as Fig. 3. The tank has approximately 1.2 *m*<sup>3</sup> (42 *ft*<sup>3</sup>) of internal volume and is designed for 100 *atm* (1500 *psi*) at a maximum working temperature of 600 *K*. Note that although the top head is flanged, access to the tank interior is not required during normal operation. The flange was necessary to provide access for the final internal surface treatment (sand-blasting) and assembly (packing installation).

This packing is used to minimize the gas temperature drop during blowdown. It consists of 340 *kg* of aluminum screen rolled up into two cylindrical rolls. Refer to Appendix A for the geometry. These rolls are supported by steel grates inside the tank. A rough calculation (Appendix A) provides an estimate of 18 *K* for the maximum temperature drop to be expected for the gas during blowdown.

Heating of the tank is effected by a large number of electrical strip heaters bolted to the tank shell, main flange and end-caps. The heating load is divided into five zones (top cap, main flange, upper shell, lower shell and lower cap), each of which can be controlled independently. Four thermocouples per zone, for a total of twenty, are mounted on the tank for monitoring, control and alarm/shutdown purposes with the redundancy deemed necessary for reliable operation. The estimated heating power is 41 *kW*. A 4.5" thick ceramic fibre blanket is used to provide heat insulation. The heating subsystem is described in further detail in Appendix A.

An injector pump arrangement is used to promote mixing of the various gases inside the tank<sup>†</sup>. The basic geometry is shown in Appendix A. The high pressure jet entrains the gas already present in the tank, setting up a recirculating flow as indicated. It is estimated that approximately one hour will be required to inject and mix the gases for a nominal run.

#### 4.3 Main shut-off valve

This valve is the primary shut-off for the 4" pipe connecting the  $H_2/NO$  Reactant Tank and the test section. It is a stainless steel, full port, 4" ball valve manufactured by the VALVTRON company (Fig. 4). It is a metal seated valve, specifically designed for high temperature gas flows. A ROTORK pneumatic actuator with a spring return is used to operate this valve. The specified opening time for the valve is 0.5 sec under full load (1,500 psi).

Further details can be found in Appendix B.

#### 4.4 Main pressure regulator

In order to maintain a constant stagnation pressure in the test section during a run, it is necessary to incorporate a pressure regulator downstream of the  $H_2/NO$  Reactant Tank. No commercially available device was found that could meet the

- i. high pressure,
- ii. high temperature,
- iii. high mass flow

and

- iv. fast response time

requirements. As a result, a prototype regulator was designed, constructed and successfully tested at Caltech. The prototype regulator led to a full scale device which is shown in Fig. 5.

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<sup>†</sup> Suggested by D. Coles.

This regulator is essentially a throttling device, in which the flow area is computer-controlled as a function of time. The valve uses two concentric cylinders, one of which (the rotor) rotates inside the other (the stator). The degree of alignment of the rotor/stator slot openings, cut into the two cylinders, controls the effective flow area and the attendant pressure drop. The regulator is designed for 100 *atm* pressure, at a maximum operating temperature of 600 *K*. Cylinder rotation is supported by a pair of high temperature ball bearings. Sealing is accomplished by graphoil gaskets at the flanges and by Teflon packing on the drive shaft. The Teflon packing is located in a special flange away from the valve housing so as to be outside of the high temperature environment.

The regulator will be actuated by a computer-controlled servomotor. The control algorithm will be closed-loop, with provisions, however, permitting open-loop (program control) operation should stability prove a problem. Preliminary calculations suggest that the high pressure delivery system may act as an undamped oscillator with a resonance frequency in the neighborhood of 25 *Hz*. The control system is being designed with a bandwidth in excess of 500 *Hz*, which should permit active damping of such oscillations during the start-up and constant flow run phases. Pressure transducers will monitor the

- a. tank pressure,
- b. the pressure in the piping section in-between the shut-off ball valve and the pressure regulating valve,
- c. the plenum delivery pressure

and, if necessary,

- d. the nozzle exit plane pressure.

The control computer\* will sense these inputs, detect deviations from the required pressure and rotate the regulator shaft accordingly.

Further details can be found in Appendix C.

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\* Digital Equipment Corp. LSI-11/73 CPU based, RT-11 operating system, equipped with a 4-channel, 16-bit, 100 *kHz* A/D system and driving a custom designed (D. Lang, A. Goudey) hardware output interface to the COMPUMOTOR servomotor actuator.

## 5. Test section

An overview of the test section is presented in Fig. 6. It is essentially a rectangular box constructed from aluminum plate\*\*. Inlet flanges provide the connections to the two gas delivery networks.

Internally, the test section is comprised of two settling chambers and flow management sections, two nozzles and a single test cell approximately two feet in length and six inches in span. This test cell is bounded by steel guidewalls on the top and bottom and by optical windows on the sides. The guidewalls are adjustable which allows the streamwise pressure gradient to be imposed or removed as necessary (Mungal & Dimotakis 1984, Hermanson & Dimotakis 1989). An outlet flange provides the connection with the downstream shower tunnel.

The nozzle contours have been machined out of aluminum blocks. These blocks are bolted into the main assembly and can be relatively easily removed and replaced by alternative contours, to change the high speed stream Mach number, for example. This is particularly important with respect to the supersonic nozzle, since it allows us to investigate a range of high speed stream Mach number flows. The subsonic contour was calculated using a GALCIT Laplace solving code for inviscid duct flow (Pepin & Dimotakis 1989). The supersonic contours were calculated using an AEDC design code (Sivells 1978). Three supersonic nozzles are currently available, designed for high speed stream nozzle exit Mach numbers (and a  $N_2$  diluent) of 1.5, 2.5 and 3.2.

Diagnostics will initially be comprised of four elements:

- o Schlieren photography,
- o static pressure measurements,
- o total pressure measurements,

and

- o total temperature measurements.

The Schlieren optics system from the subsonic facility has been retained for use with this new facility. As noted above, optical windows have been installed in the test section side plates to make photography possible. A combination of slower response but higher resolution Druck transducers, and lower resolution but faster response PCB pressure transducers have been mounted in both the top and bottom guidewalls of the test cell. The Druck transducers are intended to provide information on the streamwise pressure gradient; the

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\*\* Total test section weight is roughly 2,000 lb.

PCB transducers are installed to track the passage of shock waves, allowing a direct measurement of the convective velocity of the large scale structures for supersonic convective Mach numbers (see Papamoschou 1988, 1989 and Dimotakis 1989) to be realized thereby.

A cross-stream fixture (Fig. 7) will be used for the total pressure and temperature measurements. The fixture has two rows of tubes, one of which supports Chromel/Alumel thermocouples, the other of which is connected to a set of pressure transducers via a short length of Teflon tubing.

It should be noted that perhaps the most important diagnostic means will be provided by the total temperature probes, which, in the case of chemically reacting runs and in the limit of fast kinetics, will provide a direct measure of the *molecularly* mixed fluid in the turbulent mixing layer. This represents the unique feature of this facility, afforded by the kinetics of the  $H_2/NO/F_2$  chemical system, permitting such measurements to be made even in the highest Mach number flows that are being contemplated (see Dimotakis & Hall 1987 and Dimotakis 1989 for a more extensive discussion).

A host of additional diagnostics are also under consideration, however. In particular, redundant means of measuring the large scale structure convection velocity, a flow visualization system to assess the three dimensionality of the large scale structures in the flow, *etc.* We have deferred the development and implementation of any further diagnostic techniques, for the time being, and are awaiting for the first few experiments to provide us with the guide for any additional diagnostics that will be deemed necessary to address the fundamental problems at issue.

Further details on the test section can be found in Appendix D.

## 6. Exhaust system

The purpose of the exhaust system is to collect and cool the combustion product gases from the test section and remove the toxic and corrosive components<sup>†</sup> so that the remaining gas can be vented to atmosphere. This is accomplished with a three stage process:

1. the gas is collected in a large, inflatable catch bag;
2. the gas is sprayed with a concentrated solution of sodium hydroxide in water, which evaporatively cools the combustion products and reacts with the toxic and corrosive components (producing  $NaF$ );

and

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<sup>†</sup>  $F_2$ ,  $HF$ ,  $NO$ ,  $NOF$ ,  $NOF_x$ , etc

3. the scrubbed exhaust gases<sup>†</sup> are vented to the atmosphere.

The major hardware elements, as shown in Fig. 2, will be described below. Further details on the exhaust system can be found in Appendix E.

## 6.1 Shower tunnel

The shower tunnel connects the test section to the catch bag. It consists of an L-shaped, 30" diameter, stainless steel pipe with numerous auxiliary ports and internal components (Fig. 8). One of the auxiliary ports is an exhaust line from a safety burst diaphragm on the  $H_2/NO$  Reactant Tank. Another port is the exhaust line from the  $HF$  Turbulent Jet Facility, which is housed in the same building. Two more ports are feed lines for the internal shower systems. Another two ports serve as exhaust lines, one for gas and one for liquid. The last port is currently a spare.

The shower tunnel has a number of high pressure shower heads mounted on its centerline. These showers will spray the exhaust gases on the fly, serving to cool the hot combustion products as well as to partially neutralize of the toxic/corrosive components ( $HF$ ,  $F_2$  and  $NO$ ). This spray should also attenuate the acoustic noise resulting from the supersonic jet exhausting into the tunnel. A pair of large radius turning vanes at the corner help to turn the flow into the catch bag. The perforated cone at the tunnel exit helps to diffuse the gas entering the bag, as well as providing structural support to the bag when it is collapsed by being evacuated.

## 6.2 Catch bag

The catch bag is a box-shaped flexible membrane with an approximate capacity of  $110\text{ m}^3$  ( $3900\text{ ft}^3$ , Fig. 9). The bag material is a three-ply laminate, consisting of a polyester layer sandwiched between layers of a poly-urethane/poly-vinyl alloy. The total thickness is 0.030".

Access to the bag is through a 30" diameter opening in the bottom. A sleeve at this location allows the bag to be clamped over the end of the shower tunnel. The bag is suspended from a cantilevered frame assembly which grips the main shower feed pipe along the top of the bag. This feed pipe supplies the network of high pressure shower heads inside the bag. These showers will continue to spray after the experiment until the toxic/corrosive components in the exhaust gases have been completely neutralized.

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<sup>†</sup> Any unreacted  $H_2$ , diluted to below flammability concentrations, and any diluent gases, i.e.  $N_2$ , Ar, He etc.

### 6.3 Shower pump

Two pumps of widely different sizes are available to feed the showers inside the shower tunnel and the catch bag. Only one pump is used at a time, depending on the requirements of the experiment. The high pressure pump has a nominal output of 60 *gpm* at 300 *psi*; the low pressure pump has a nominal output of 20 *gpm* at 30 *psi*. There are two different reservoirs that can independently supply the pump. One is the solution of *NaOH* in water used to neutralize/scrub the exhaust gases. The other is pure water which is used after the run to wash the pump/shower system and thereby prevent the build-up of salts.

### 6.4 Exhaust blower

A high capacity, corrosion resistant blower is used to pump the exhaust gases out of the catch bag and into the atmosphere. The feed line to the blower has two inputs: one from the catch bag and one from the atmosphere. This atmospheric feed allows us to mix the exhaust gases with air before venting. This option will be used to dilute the unreacted hydrogen gas below the flammability limit.

## 7. Facility control system

This facility employs a mixture of manual and automatic controls. While the mix between these two can be changed, as deemed optimal in the future, the initial mix has been dictated by the operating experience of the subsonic facility, which we believe should serve as a good guide. Essentially all of the gas loading and venting operations are manual. A control panel has been constructed (Fig. 10) in order to collect most of the necessary valves, switches and gauges in one location. Automatic facility monitoring and control, with a  $\mu$ VAX computer, will be used for four operations:

- o monitoring of the  $H_2/NO$  Reactant Tank heating subsystem,
- o communication with the control computer of the main pressure regulator,
- o run time operation of the gas delivery network shut-off valves,

and

- o sequencing the data acquisition system\*.

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\* A DEC LSI-11/73 CPU based, RT-11 computer, with  $2 \times 32$  channels of 12-bit, 200 *kHz* each, A/D converters, networked *via* ETHERNET to the pressure regulator control computer and the facility control computer.

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**Table 1: Physical Parameters And  
Predicted Performance Specifications**

Supersonic Stream:	Reactant Gases	H <sub>2</sub> , NO
	Diluent Gases	N <sub>2</sub> , He, Ar
	Mach Number Range	1.5 < $M$ < 3.2 (for N <sub>2</sub> )
		1.5 < $M$ < 2.7 (for N <sub>2</sub> )
	Stagnation Temperature	300 < $T$ < 600 (Kelvin)
	Nozzle Exit Dimensions	1.25 in by 6.0 in
Subsonic Stream:	Reactant Gas	F <sub>2</sub>
	Diluent Gases	N <sub>2</sub> , He, Ar
	Mach Number Range	0 < $M$ < 0.3
	Stagnation Temperature	300 Kelvin (ambient)
	Nozzle Exit Dimensions	2.0 in by 6.0 in
General Parameters:	Nominal Run Time	3 sec
	Test Section Static Pressure	1 atm
	Test Section Length	24 in
	Max. Convective Mach Number	2
	Max. Shear Layer $Re_\delta$	6 × 10 <sup>6</sup> (for N <sub>2</sub> ) 2 × 10 <sup>6</sup> (for He)

FIGURE 1:

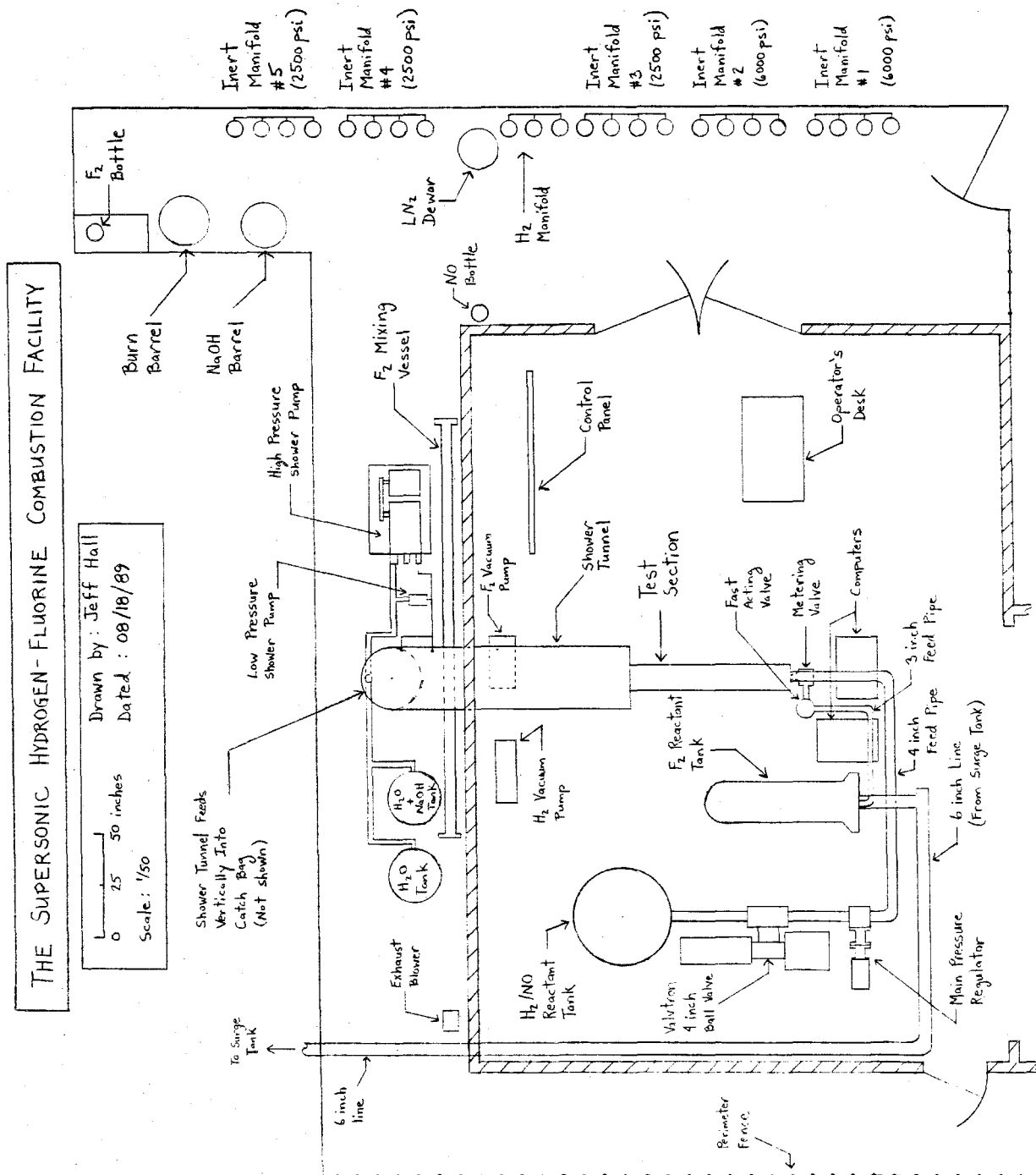


FIGURE 2:

THE SUPERSONIC HYDROGEN-FLUORINE COMBUSTION FACILITY: OVERALL PLUMBING SCHEMATIC

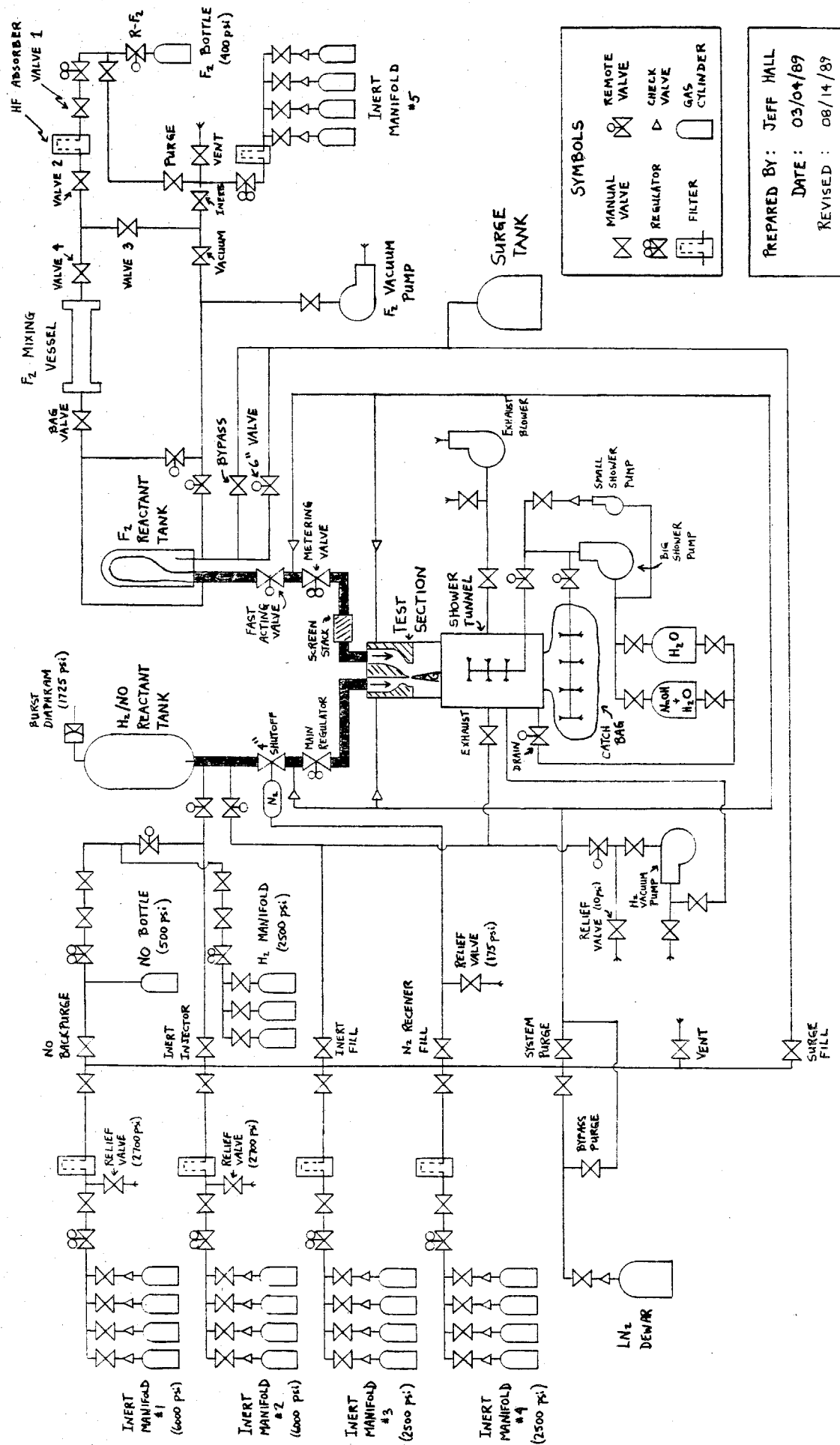


FIGURE 3:

H<sub>2</sub>/NO REACTANT TANK

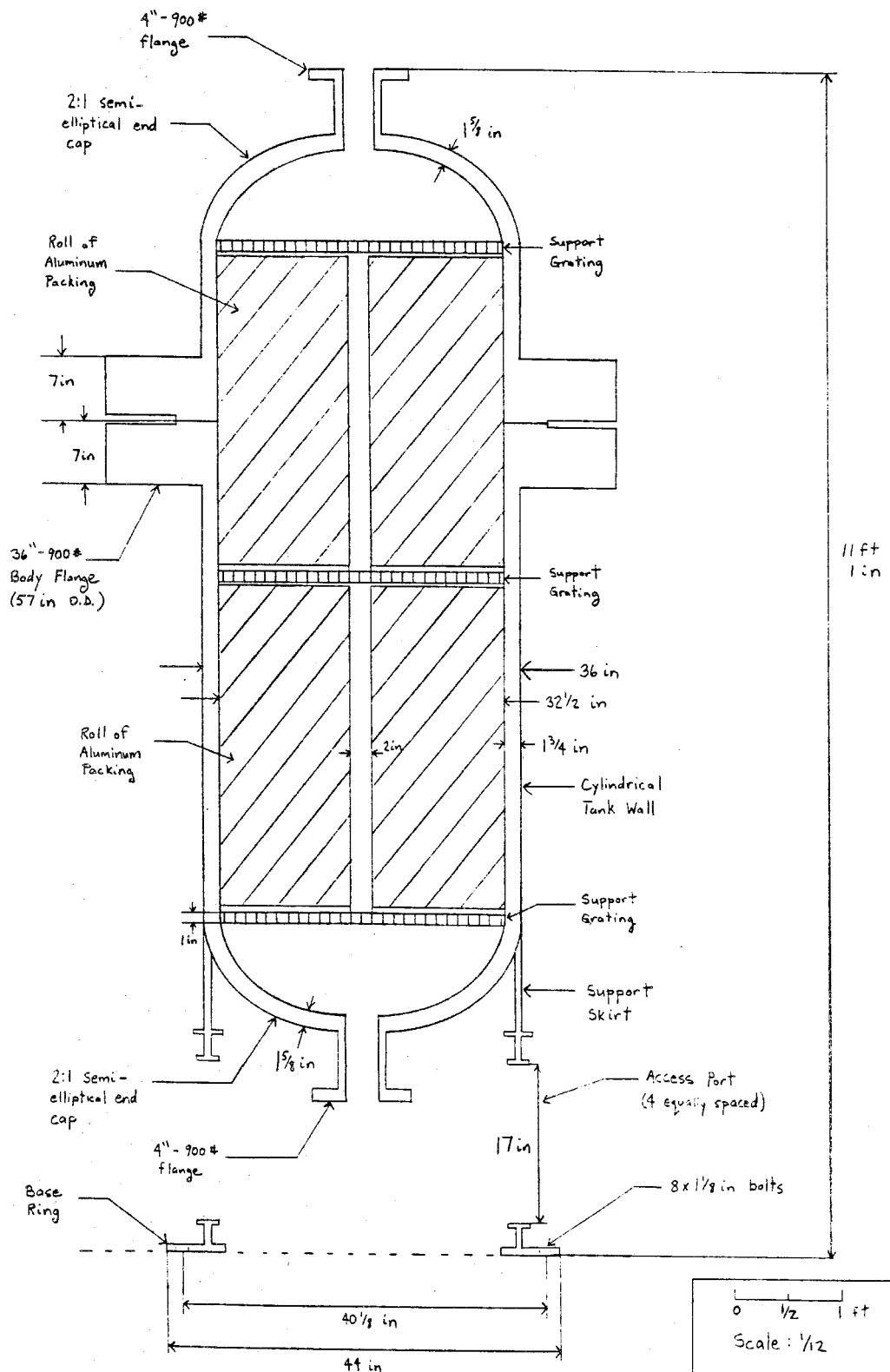
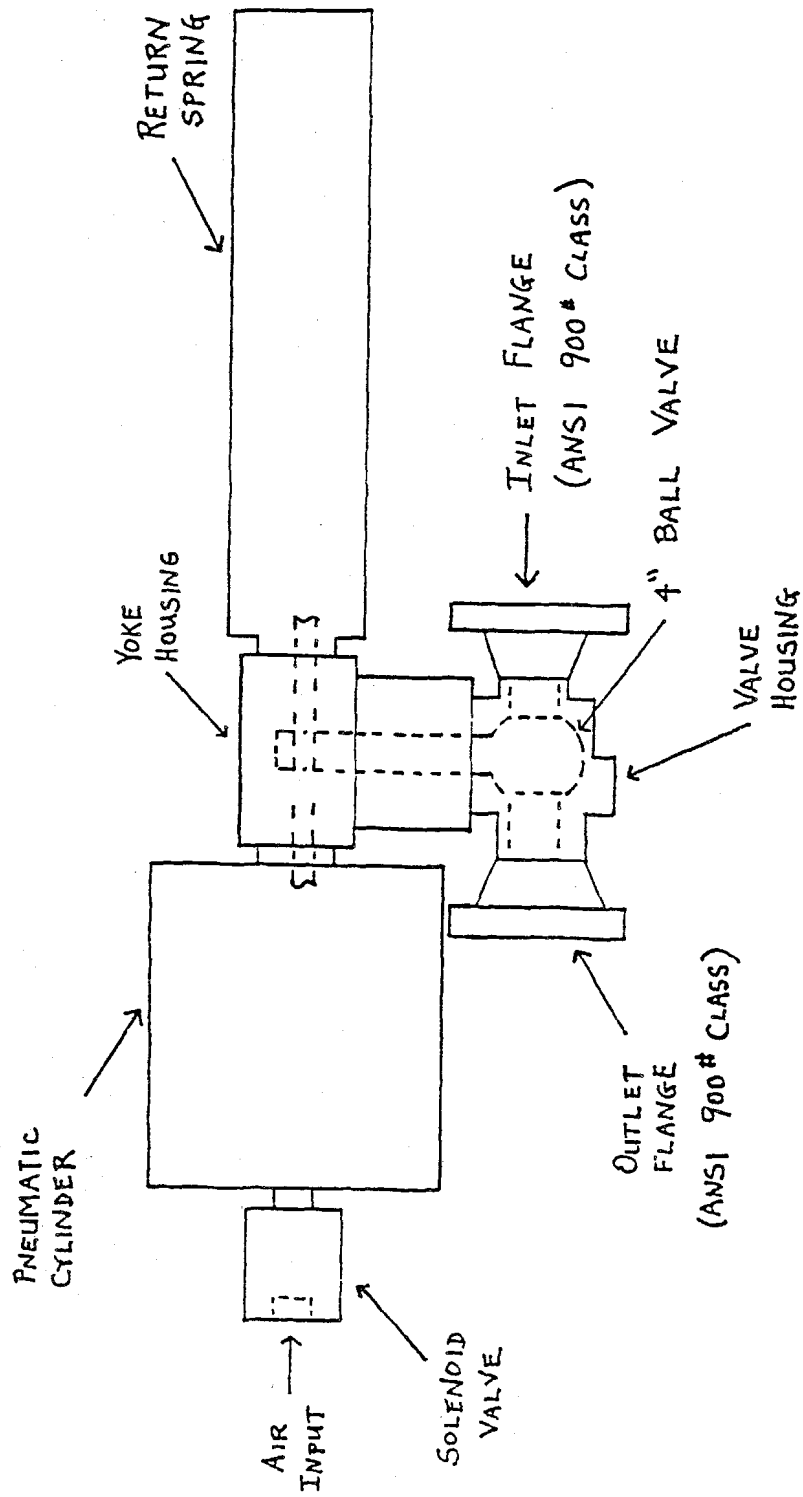
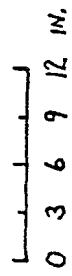


FIGURE 4: MAIN SHUT-OFF VALVE

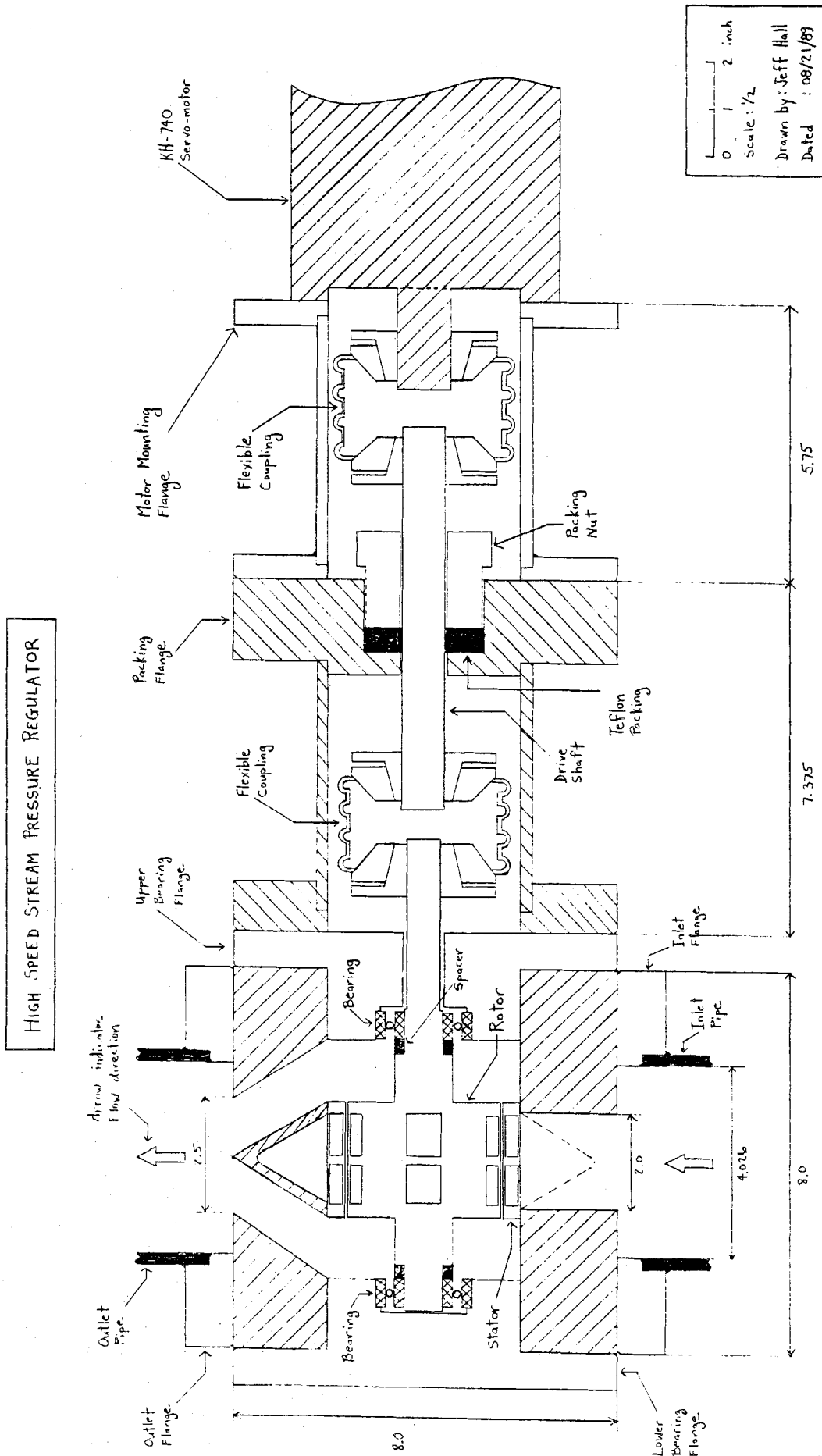


SCALE:  $\frac{1}{12}$



VALVTRON FULL PORT 4" BALL VALVE  
 ROTORK 325-17SR ACTUATOR

FIGURE 5:



# FIGURE 6:

## BISONIC SHEAR LAYER TEST SECTION: FOUR-VIEW ASSEMBLY DRAWING

APPROX SCALE: 0 1 2 INCHES

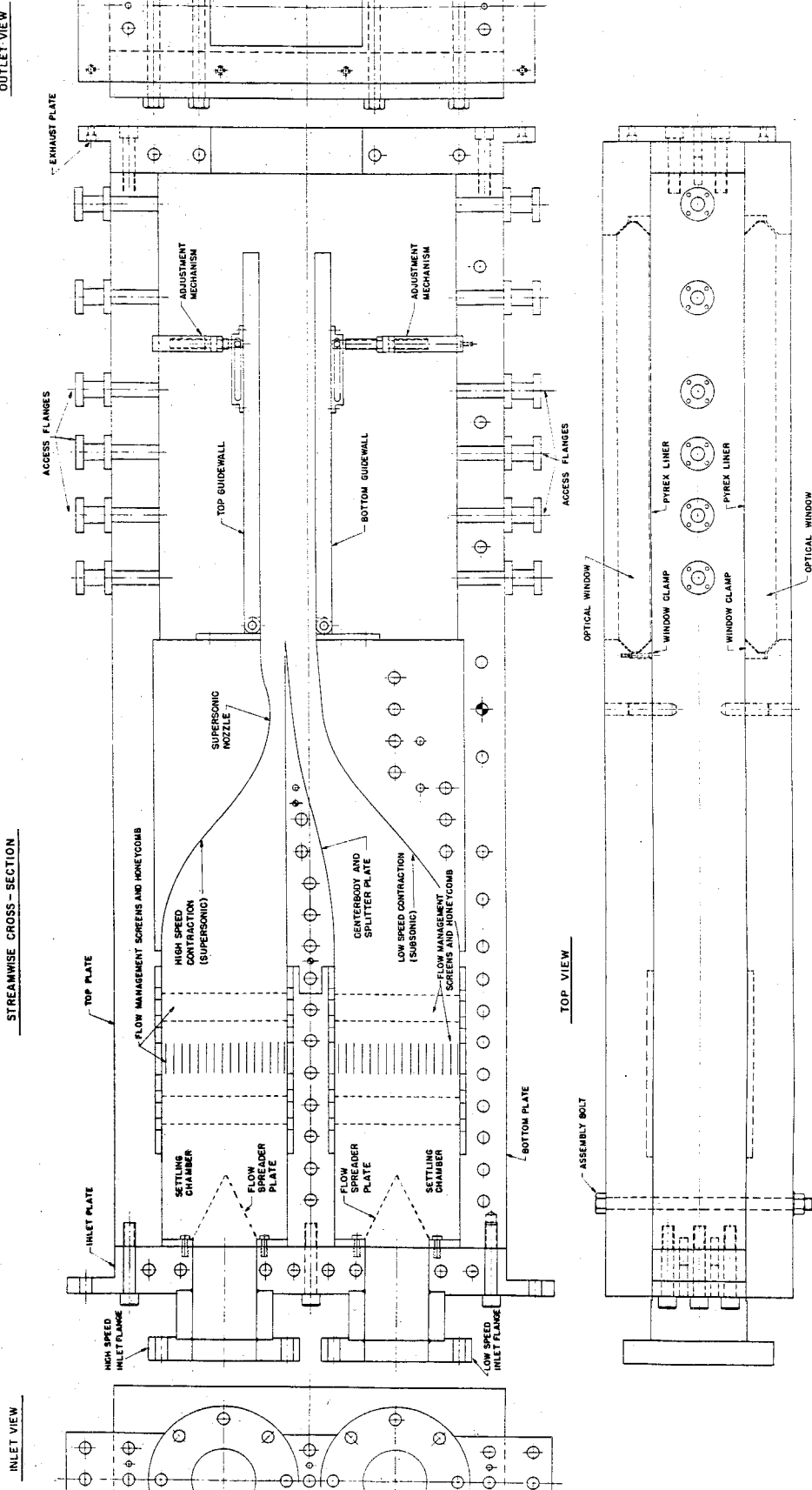




FIGURE 7:  
CROSS - STREAM INSTRUMENT RAKE

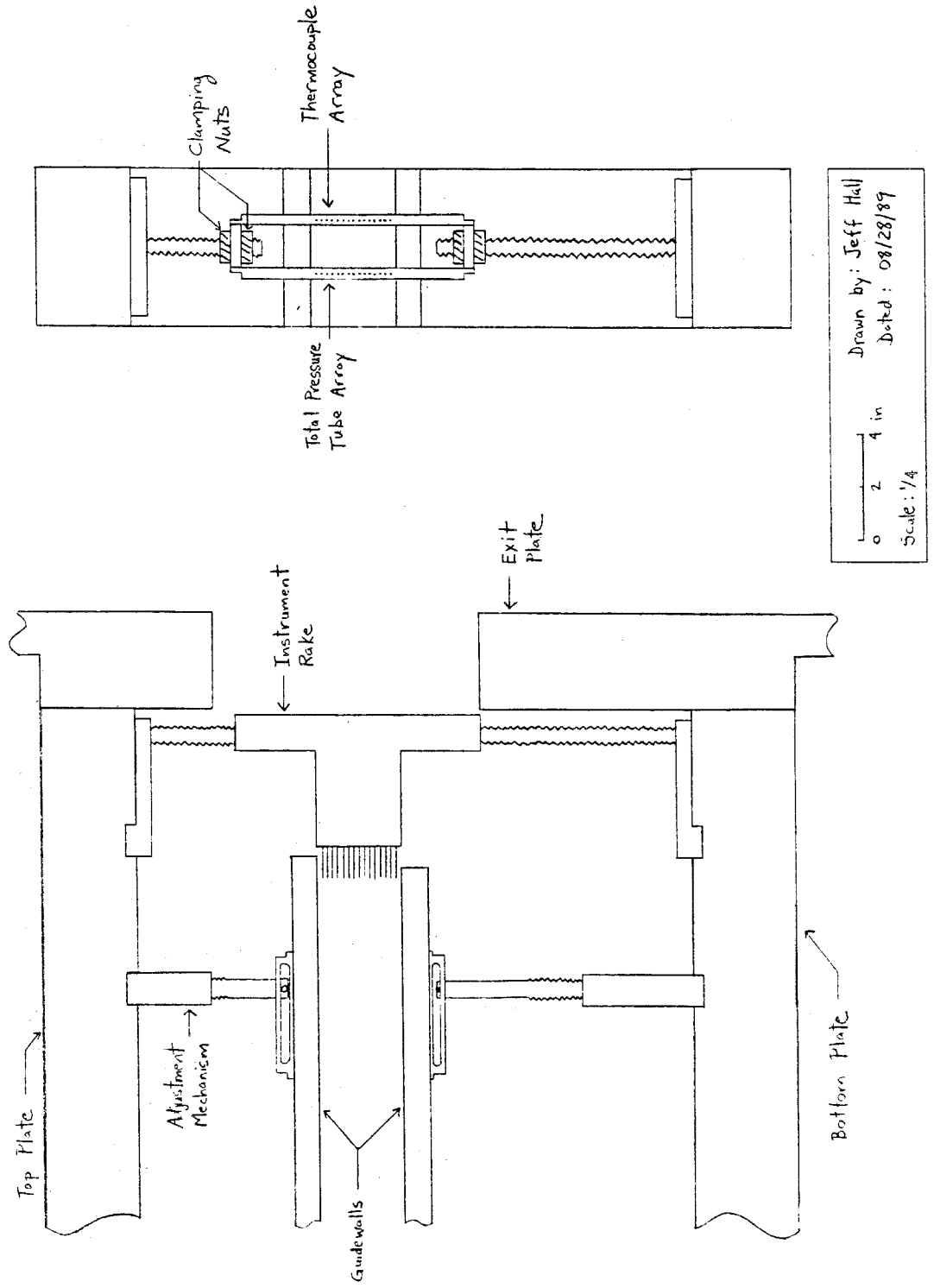
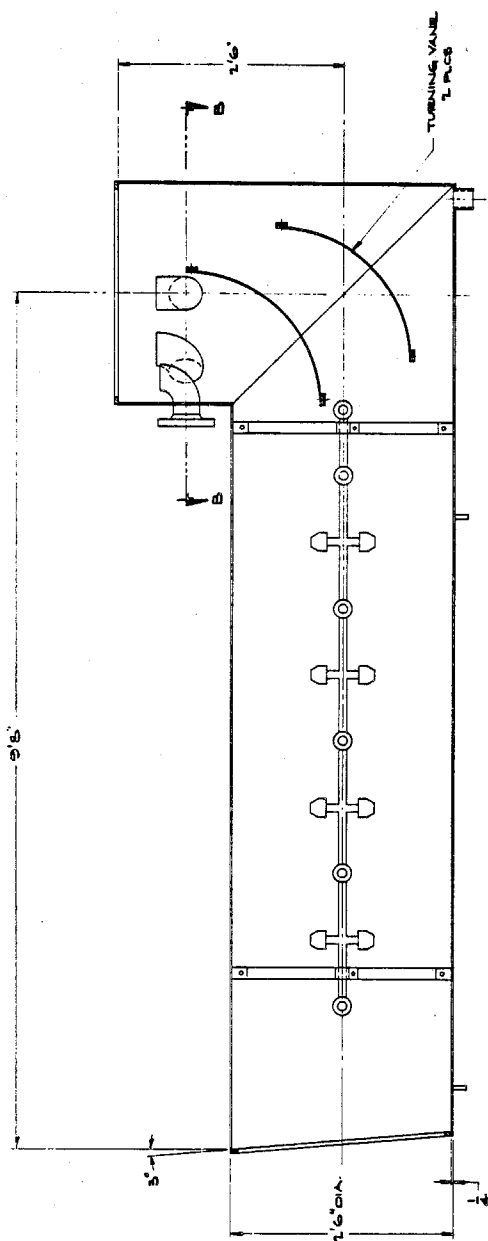
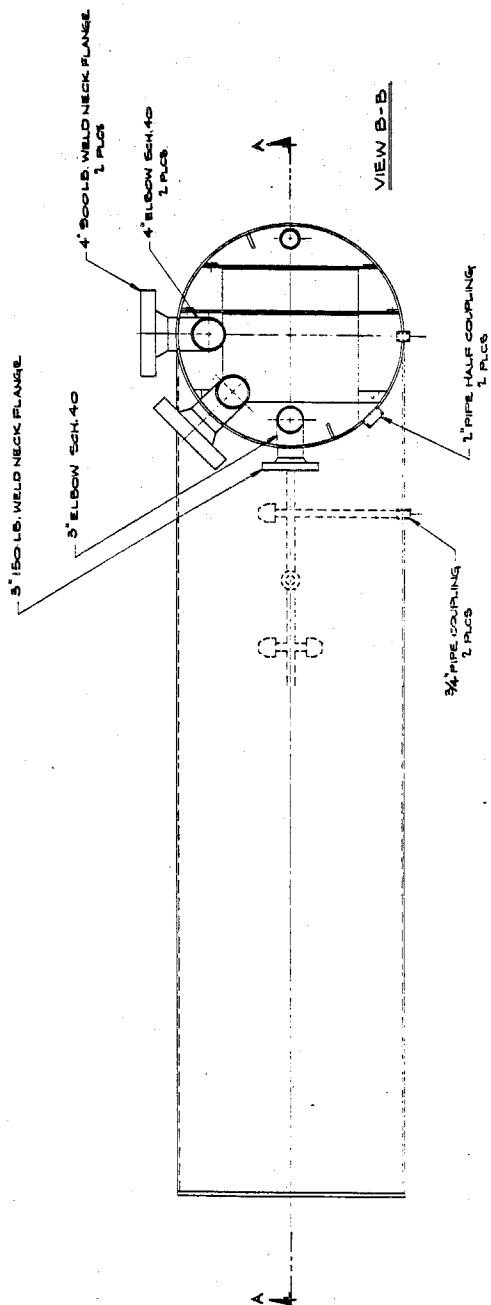
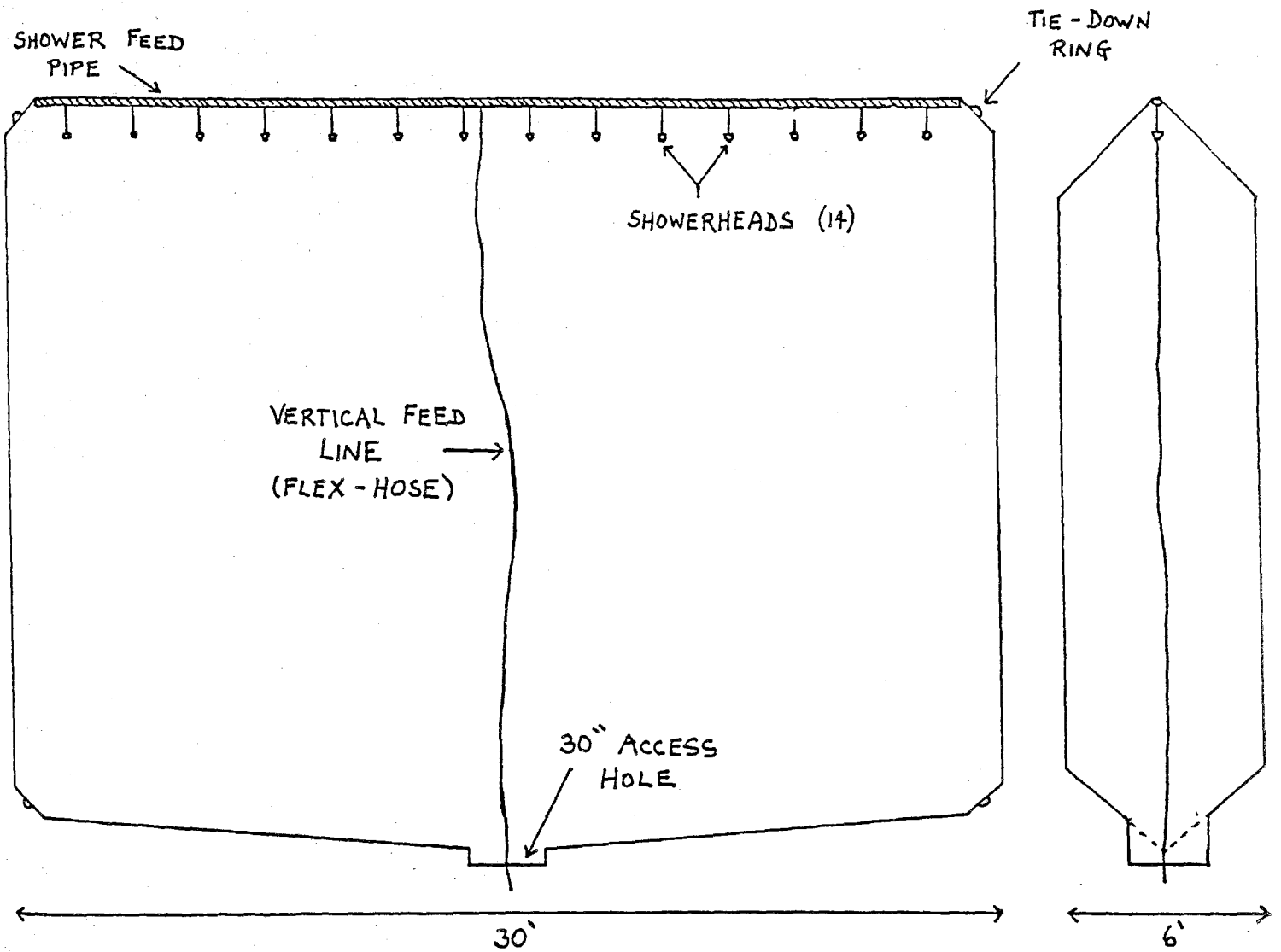


FIGURE 8: SHOWER TUNNEL



COMBUSTION LAB SHOWER TUNNEL

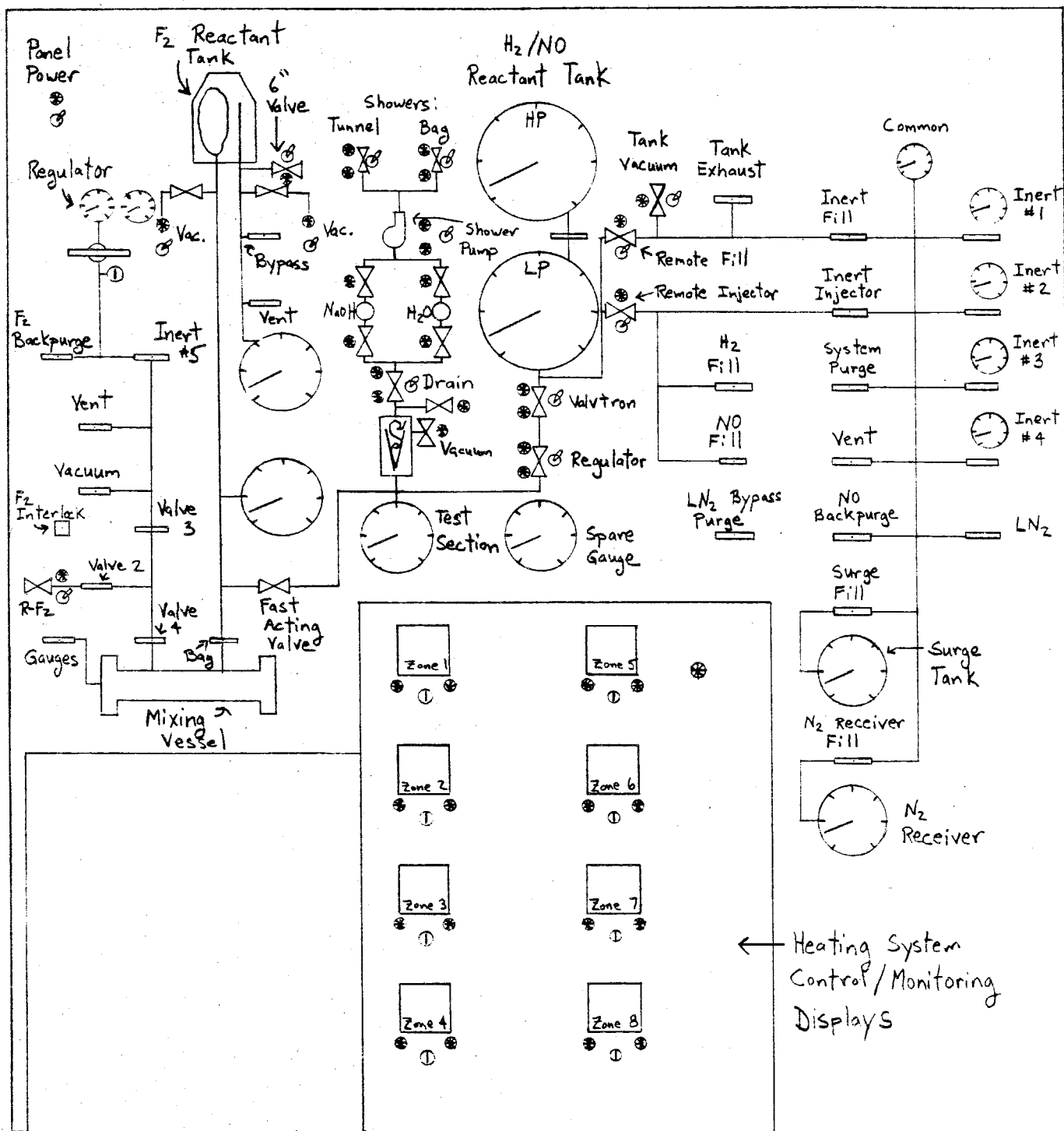
FIGURE 9: CATCH BAG



SCALE:  $\frac{1}{60}$  0 1 2 3 4 5 ft.

BAG IS SHOWN INFLATED.

# FIGURE 10: CONTROL PANEL



0 1/2 1 ft

Scale: 1/12

Drawn by: Jeff Hall

Dated: 08/23/89

Symbols:

- |  |                |  |                   |
|--|----------------|--|-------------------|
|  | Valve Handle   |  | Electrical Switch |
|  | Remote Valve   |  | Indicator Light   |
|  | Pressure Gauge |  | Tubing Graphic    |

Heating System Control/Monitoring Displays

## Appendix A: H<sub>2</sub>/NO Reactant Tank

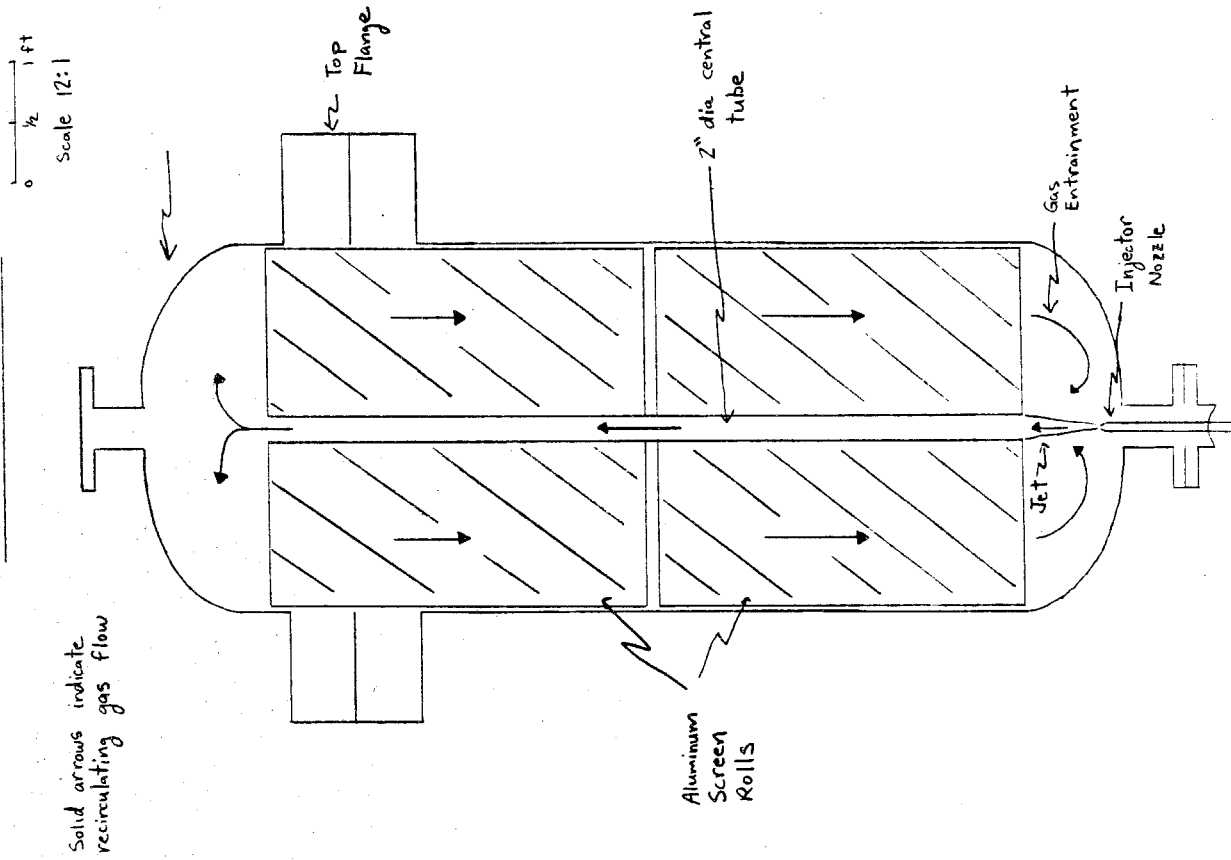
This appendix describes the H<sub>2</sub>/NO Reactant Tank in greater detail. The information provided consists of:

- General specifications (this page).
- Injector geometry and mixing analysis.
- Calculation of blowdown temperature drop.
- Heating system drawings, circuit diagrams and heater data.

### General Specifications:

Manufacturer:	South Gate Engineering Inc.
Serial No.:	8308
Working Pressure:	1500 psi at 650 °F
Hydrostatic Test Pressure:	2250 psi
Material:	SA516 – 70 steel (shell and heads)
Wall Thickness:	1.75 in (shell); 1.625 in (heads)
Overall Length:	137 in (including support skirt)
Nominal O.D.:	36 in
Internal Volume:	42.8 ft <sup>3</sup>
Estimated Weight:	14,100 lbs

## INJECTOR GEOMETRY



## INJECTOR ANALYSIS

Model the injector as a turbulent jet with a negligible pressure gradient. The relevant formulae are (Chen & Rodi, 1980):

$$\frac{\delta}{x} = 0.44 \quad (1) \quad \text{growth rate} \quad E \equiv \frac{\dot{V}}{\dot{V}_j} = 0.32 \frac{x}{d} \quad (2) \quad \text{entrainment (molar)}$$

$$\text{Set } E = 20 \quad \therefore \frac{x}{d} = 62.5 \quad (3)$$

Now,  $\delta = 5 \text{ cm}$  (diameter of central tube) (4)

$\therefore x = 11.4 \text{ cm}$  (injector-tube separation) (5)

and  $d = 1.8 \text{ mm}$  nozzle orifice diameter (6)

The tank is to be filled ( $10^7 \text{ Pa} \approx 4.2 \text{ knoles of } N_2$ ) over a 1 hour period.

$$\therefore \dot{V}_j = 4.2 \text{ knol} / 3600 \text{ sec} \Rightarrow \boxed{\dot{V}_j = 1.17 \times 10^{-3} \text{ knol/sec}} \quad (7)$$

This value for  $\dot{V}_j$  is attainable with  $d = 1.8 \text{ mm}$  without choking the nozzle. (Not shown here.)

Let's estimate the concentration gradient (top to bottom) resulting from this technique. Start with  $N_2$  knoles of gas A in the tank and add ( $N_2/E$ ) knoles of gas B via the injector. The ideal result will be a perfectly mixed gas with concentration

$$C(A) = \frac{N_2}{N_2 + N_2/E} = \frac{E}{E+1} \quad (8)$$

After  $i$  such "turnovers" the concentration of the gas A in the tank is

$$C_i(A) = \left(\frac{E}{E+1}\right)^i \quad (9)$$

Now, the difference between successive "turnovers" will be a measure of the concentration gradient.

$$\Delta C_i = C_i - C_{i-1} = C_{i-1} \left(\frac{E}{E+1}\right) - C_{i-1} \Rightarrow \boxed{\frac{\Delta C_i}{C_{i-1}} = \frac{-1}{E+1}} \quad (10)$$

$$\text{For } E=20, \quad \frac{\Delta C_i}{C_{i-1}} = \frac{-1}{21} \quad \text{or} \quad \boxed{\frac{\Delta C_i}{C_{i-1}} \approx 5\%} \quad (11)$$

# H<sub>2</sub>/NO REACTANT TANK INJECTOR AND FILL LINE

Dated: 05/24/89

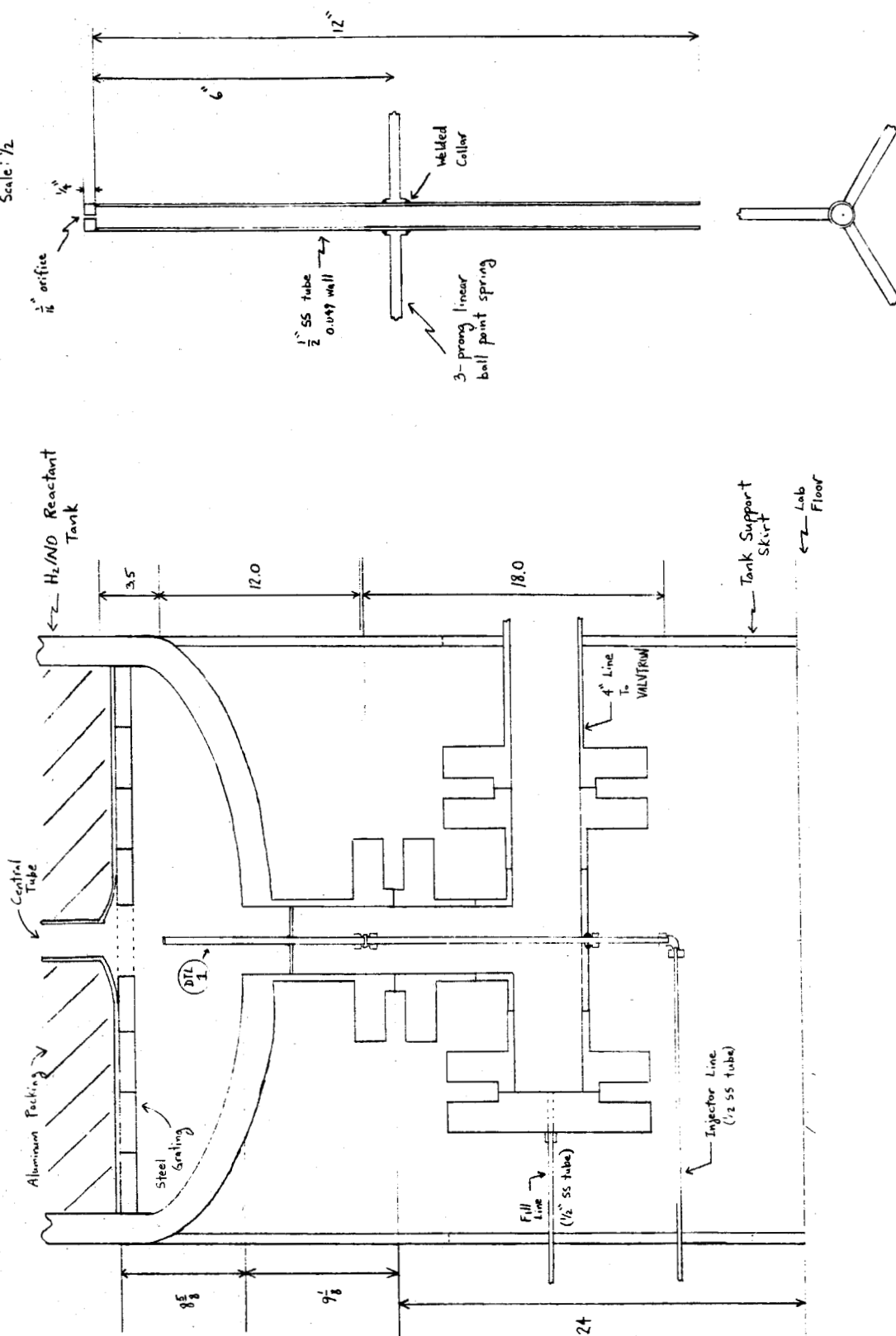
Revised: 08/21/89

Drawn by: Jeff Hall

Scale: 1/4

Detail 1: Injector Tube

Scale: 1/2



## APPENDIX A: PACKING EFFECT ON TANK TEMPERATURE DROP - SAMPLE CALCULATION

ASSUMPTION: SCREEN PACKING AFFORDS PERFECT HEAT TRANSFER TO GAS. (HIGH SURFACE AREA TO VOLUME RATIO.) THEREFORE, PACKING TEMPERATURE EQUALS GAS TEMPERATURE.

A CONTROL VOLUME ANALYSIS OF THE GAS IN THE TANK YIELDS:

$$\frac{d}{dt}(C_v T M) - C_p T \frac{dM}{dt} = \dot{Q}$$

WHERE  $M$  = MASS OF GAS  
 $\dot{Q}$  = HEAT TRANSFER RATE FROM PACKING TO GAS  
 $T$  = TEMPERATURE

$$M C_v \frac{dT}{dt} + C_v T \frac{dM}{dt} - C_p T \frac{dM}{dt} = \dot{Q}$$

$$M C_v \frac{dT}{dt} - R T \frac{dM}{dt} = \dot{Q}$$

ASSUME  $T \approx$  CONSTANT AND INTEG

$$\Rightarrow R T (\Delta M) = \Delta Q$$

$$\text{BUT } \Delta M = \frac{\Delta P V}{R T}$$

$$\therefore \boxed{\Delta P V = \Delta Q}$$

DATA:  $V \approx 1.1 \text{ m}^3$  (GAS VOLUME)  
 $\Delta P \approx 50 \text{ ATM}$  ( $5 \times 10^6 \text{ Pa}$ )

$$\therefore \boxed{\Delta Q \approx 5.5 \times 10^6 \text{ J}}$$

BUT  $\Delta Q = M C_p \Delta T_p$  FOR THE PACKING

$$\therefore \Delta T_p \approx \frac{\Delta Q}{M C_p}$$

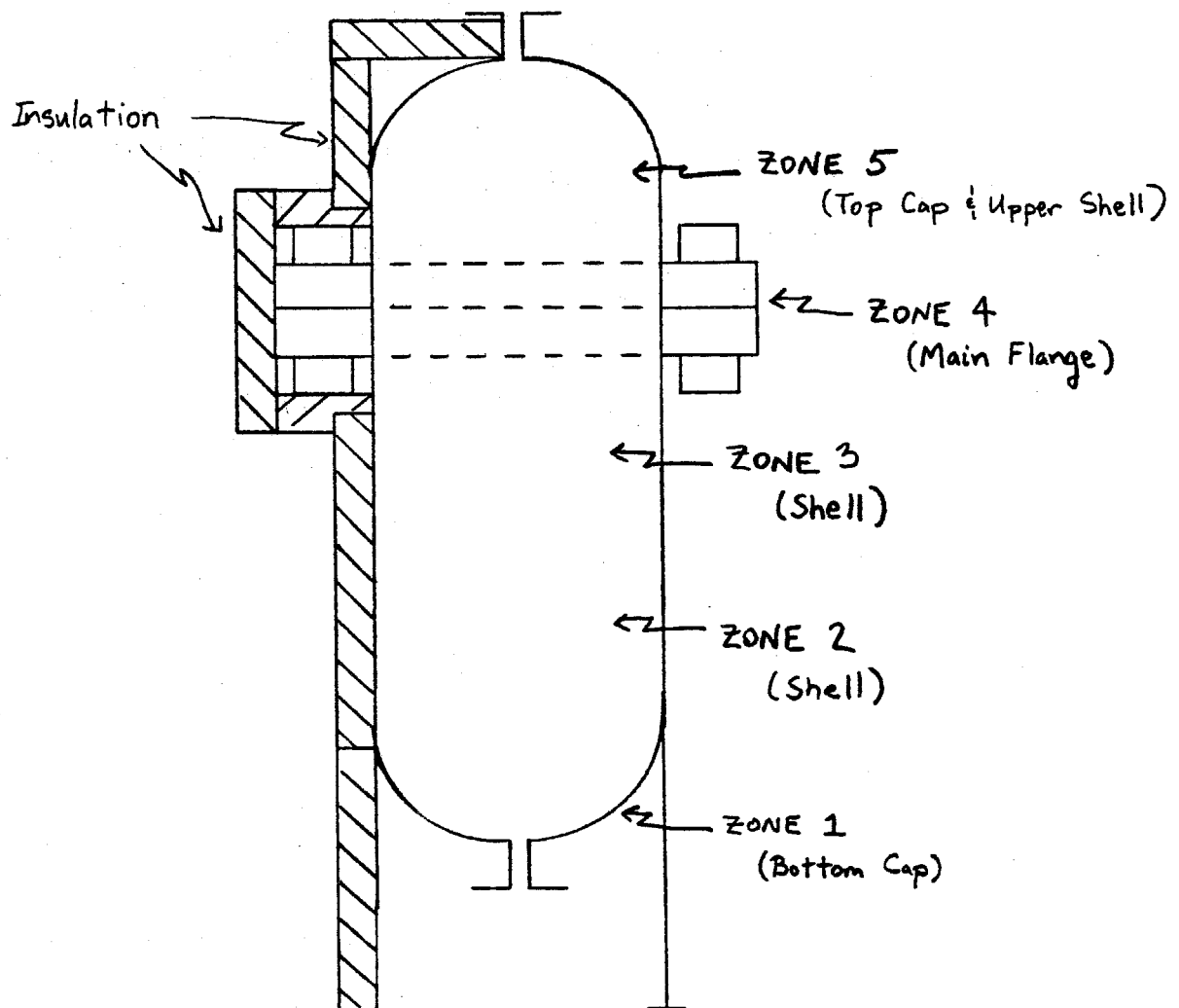
DATA:  $M = 340 \text{ kg}$   $C_p \approx 900 \text{ J/kg} \cdot \text{K}$

$$\therefore \boxed{\Delta T_p = 18 \text{ K}}$$

HENCE, THE PACKING TEMPERATURE WILL DROP BY 18 K, AND VIA THE ORIGINAL ASSUMPTION, SO WILL THE GAS. NOTE THAT THIS IGNORES THE HEAT TRANSFER FROM THE TANK WALL AND THE DELIVERY PIPE.



HYDROGEN REACTANT TANK: OVERVIEW  
OF HEATING SUB-SYSTEM AND  
INSULATION

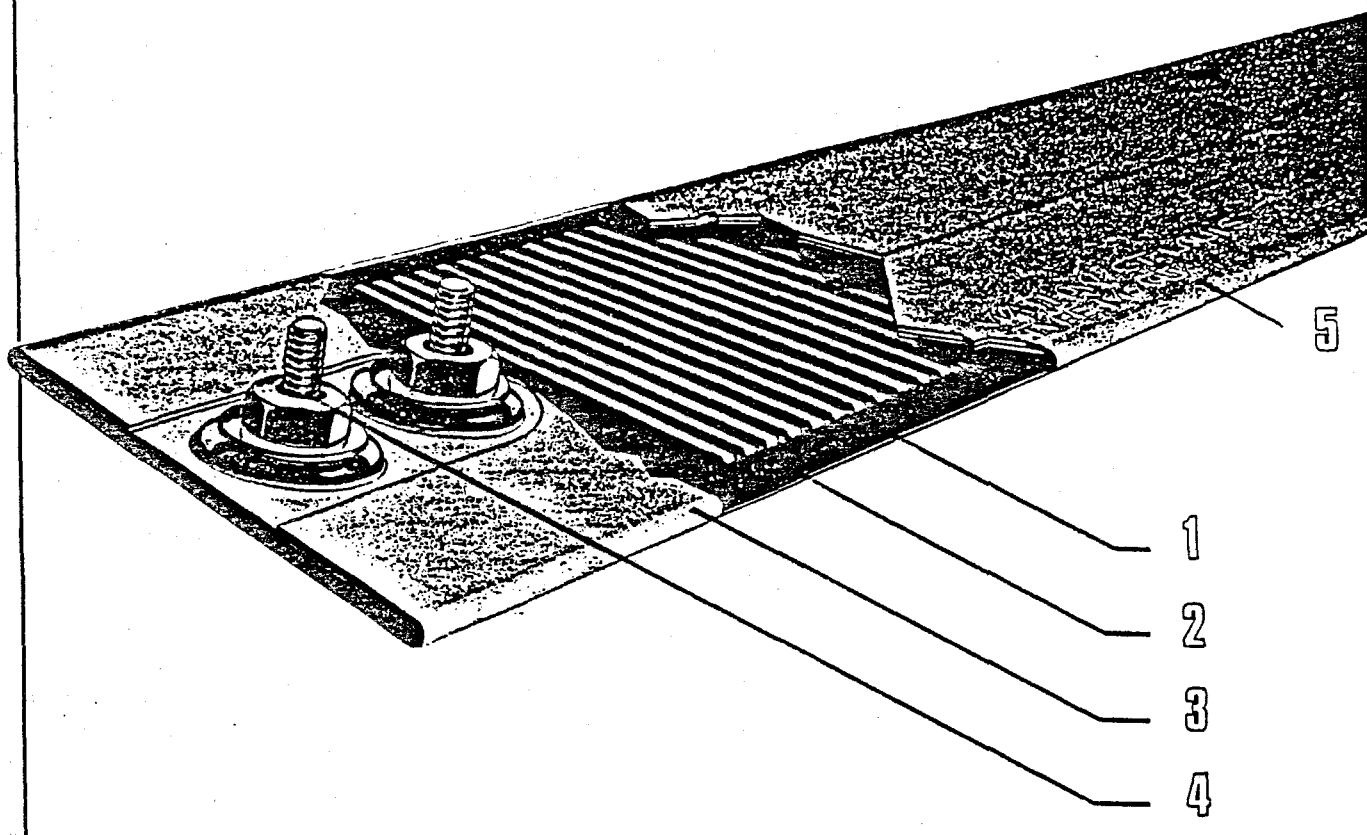


Dated: 08/28/88

NOTES:

- 1) See other drawings for detailed heater layouts in each zone.
- 2) Insulation is Kaowool ceramic fibre blanket,  $1\frac{1}{2}$  inch thick.  
Three layers are used for an overall  $4\frac{1}{2}$  inch thickness
- 3) The tank is oriented such that  $0^\circ$  azimuthal is pointing north.  
(That is, the side of the tank through which the wires penetrate the insulation.)

# Mica Strip Heaters



- An economic and reliable source of heat for industrial equipment.
- UL Component Recognition Available. Watlow Mica Strip Heaters have met strict UL requirements for applications up to 900°F sheath temperature.

- 53 Stock Models. Immediate shipment of popular sizes and ratings.
- Special Engineering. Watlow designs heaters to meet specific application requirements.
- Low Mass Design. Fast heat-up and response to control.

1

The flat resistance ribbon generates heat over a broad area. This design puts the heat source closer to the work.

Each Strip Heater design is carefully engineered with the aid of computer programs. This assures the best combination of ribbon gauge, total wattage and winding spacing for maximum heat transfer and long life.

2

A 100% inspection of incoming mica assures excellent dielectric strength. A strip just 15 mils (.4mm) thick on both sides of the resistance element provides complete electrical insulation.

Yet, mica that thin offers very little resistance to the efficient flow of heat. And its low mass allows the heater to respond quickly to control.

Mica also withstands high voltage spikes, resists moisture and is inert to most chemicals.

3

The rust-resistant zinc-coated steel sheath material is treated for improved emissivity. Since heat is essentially radiated to the work, this is an important factor in heating efficiency. The strength of this material gives the unit overall rigidity. Heaters can be provided with a stainless steel sheath for resistance to more corrosive atmospheres.

4

Nickel-plated steel terminal posts are securely riveted for a positive trouble-free connection to the resistance circuit.

5

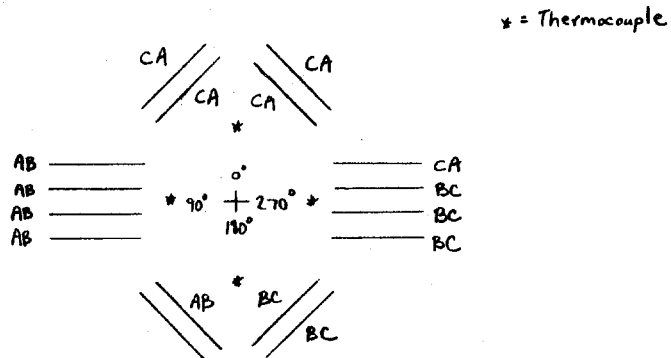
If you are a designer/manufacturer of equipment which requires UL approval, using approved Watlow Mica Strip Heaters will help.

All constructions and options presented in this section are covered under UL's Recognition and Follow-Up Services. File Number E52751.

# ELECTRICAL NETWORK : ZONE 1 (BOTTOM CAP)

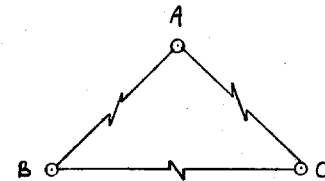
Dated: 08/31/88

## Geometrical Layout



16 Bottom Cap Heaters, type SIJ6A113 (240V, 200W)  
(1 not connected)

## Circuit Details



Nominal Resistance : 260Ω - 300Ω

Circuit Resistances:

Leg AB = 37.1 Ω

Leg BC = 36.8 Ω

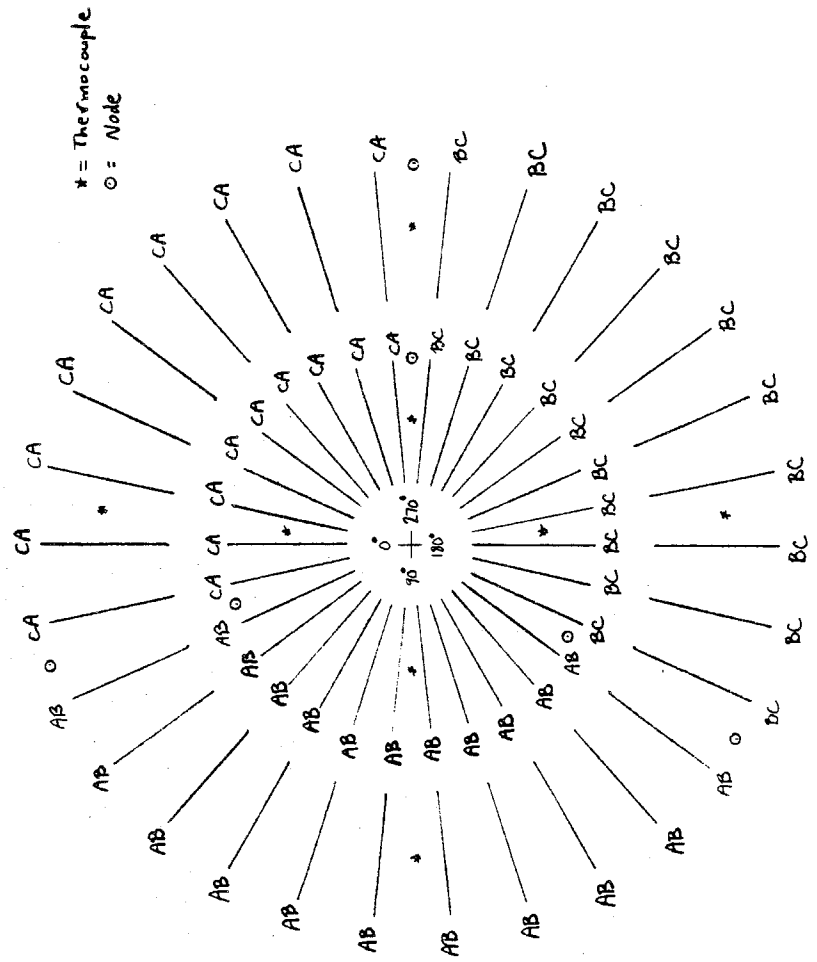
Leg CA = 37.1 Ω

Total Power = 3.0 kW

# ELECTRICAL NETWORK : ZONES 2 AND 3 (TANK SHELL)

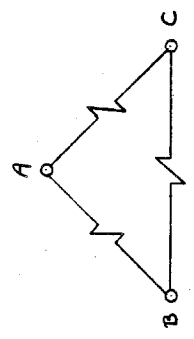
Dated: 08/26/88

## GEOMETRICAL LAYOUT



ZONE 2 : Outer Circle (Lower ring on tank), 30 SIJ21AR2 heaters  
 ZONE 3 : Inner Circle (Upper ring on tank), 30 SIJ21AR2 heaters

## CIRCUIT DETAILS



3-phase delta configuration  
 Nominal heater resistance: 173  $\Omega$  - 200  $\Omega$   
 Heater rating: 240V 300W

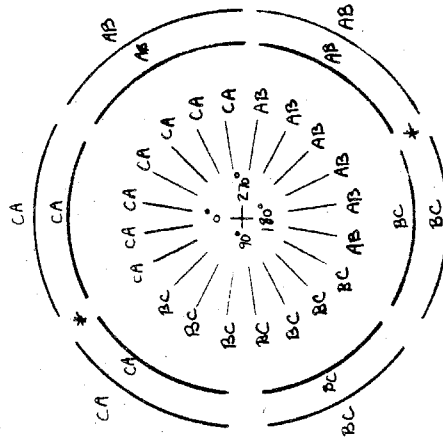
Zone 2:  
 Leg AB Resistance = 12.4  $\Omega$  (10 heaters)  
 Leg BC Resistance = 12.4  $\Omega$  "  
 Leg CA Resistance = 12.4  $\Omega$  "  
 Total Power = 9 kW

Zone 3:  
 Leg AB Resistance = 12.4  $\Omega$  (10 heaters)  
 Leg BC Resistance = 12.4  $\Omega$  "  
 Leg CA Resistance = 12.4  $\Omega$  "  
 Total Power = 9 kW

# ELECTRICAL NETWORK : ZONE 4 (MAIN FLANGE)

Dated: 08/27/88

## TOP FLANGE

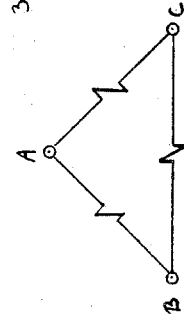


12 circumferential heaters,  
type SIJ29AX1 (240V, 200W)

20 top surface heaters  
type SIJ7AU3 (240V, 200W)

\* = Thermocouple

## CIRCUIT DETAILS



Nominal Resistances:

- 1) Type SIJ29AX1 : 260  $\Omega$  - 300  $\Omega$
- 2) Type SIJ7AU3 : 260  $\Omega$  - 300  $\Omega$

Circuit Resistances:

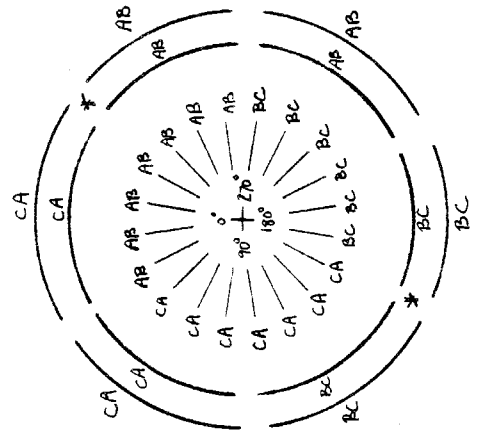
Leg AB = 10.3  $\Omega$

Leg BC = 10.3  $\Omega$

Leg CA = 10.0  $\Omega$

Total Power : 14.4 kW

## BOTTOM FLANGE



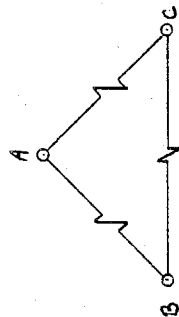
12 circumferential heaters  
type SIJ29AX1 (240V, 200W)

20 bottom surface heaters  
type SIJ7AU3 (240V, 200W)

# ELECTRICAL NETWORK : ZONE 5 (TOP CAP & SHELL)

Dated: 08/27/98

## Circuit Details



3-Phase delta configuration

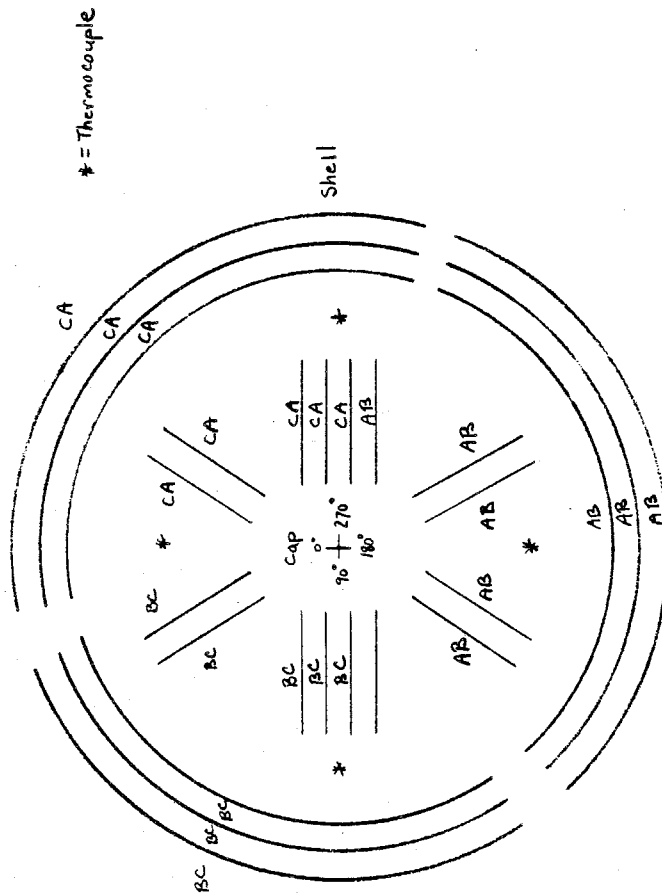
### Nominal Resistances:

- 1) Type SIJ30AU1 :  $173\Omega - 200\Omega$
- 2) Type SIJ6AU13 :  $260\Omega - 300\Omega$

### Circuit Resistances:

- Leg AB =  $18.1\Omega$   
 Leg BC =  $19.2\Omega$   
 Leg CA =  $19.2\Omega$

Total Power =  $5.9\text{ kW}$



- 9 Top Shell heaters,  
 type SIJ30AU1 (240 V, 300w)  
 16 Top Cap heaters,  
 type SIJ6AU13 (240 V, 200w)

## Appendix B: VALVTRON Shut-Off Valve

This appendix describes the VALVTRON shut-off valve and its ROTORK actuator in greater detail. The information provided consists of:

- General specifications (this page).
- Drawing of valve.
- Cut-away picture of the actuator.

### General Specifications:

Valve Type:	VALVTRON #TB721P040AAA ball valve
Valve Size:	4 inch (full port)
Material:	316 SS (plus coatings)
Design Pressure:	1500 psi at 650 °F
Actuator Type:	ROTORK #325 - 17SR
Operation:	Pneumatic pressure to open, spring return
Nominal Opening Pressure:	80 psi
Nominal Opening Time:	0.5 sec.
N <sub>2</sub> Receiver Volume:	13.4 gals. (50.9 litres)
Estimated Weight:	1,400 lbs (valve + actuator)

Note that the pneumatic cylinder of the actuator requires a source of gas. We use a small tank full of nitrogen, sized such that the final pressure during operation is 80 psi (which requires a starting pressure of 170 psi). In practice, the actuator will work with a final pressure as little as 50 psi, albeit with a corresponding opening time of approximately 3 seconds.

# DESIGN SIMPLICITY SOLVES PROBLEMS

**Seat integral**  
No movement under pressure

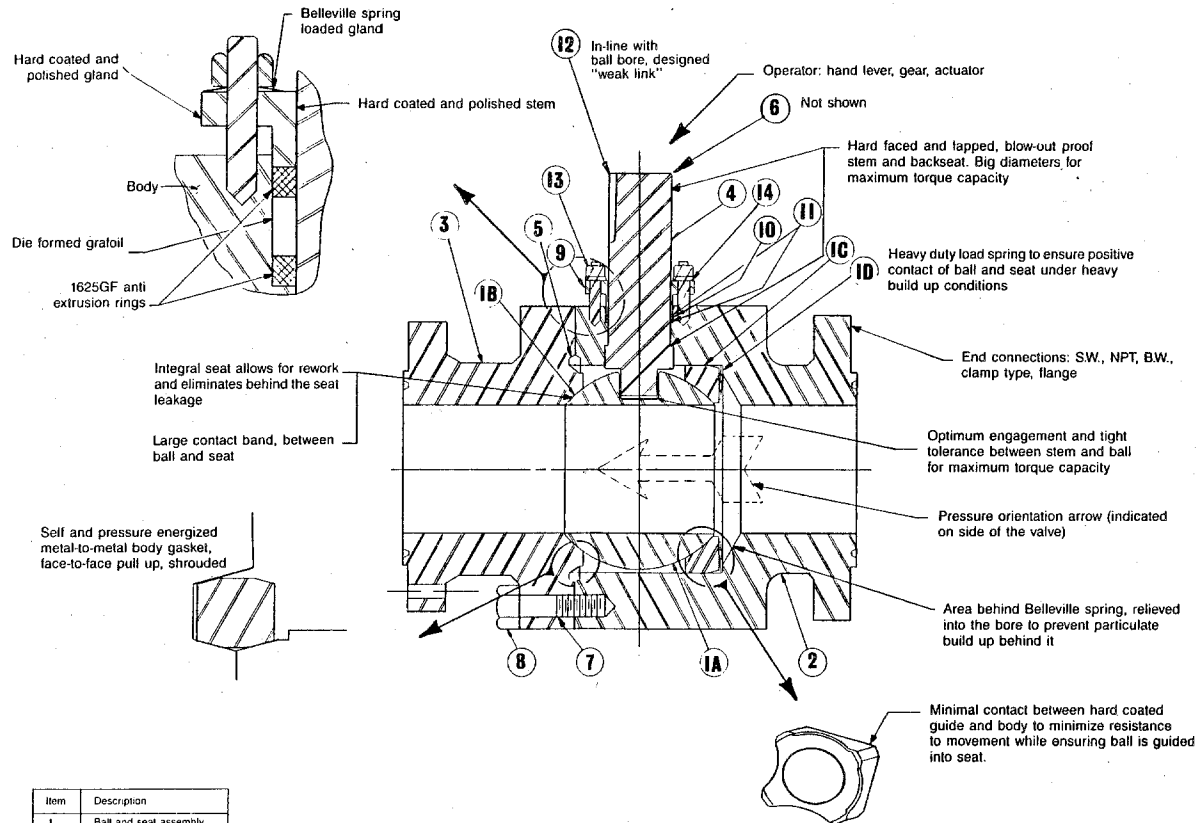
**No seat-to-body leak path**

**All metal-to-metal**

**No separate seat**  
to cock due to guide design

**No behind the seat cavity**  
for particulate packing

**All seal faces coated** as standard



Item	Description
1	Ball and seat assembly
1A	Ball
1B	Seat
1C	Guide
1D	Spring
2	Body
3	End piece
4	Stem
5	Body gasket
6	Stem stop drive nut
7	Body stud
8	Nut
9	Gland ring
10	Gland packing (die formed grafoil)
11	Gland packing (braided graphite)
12	Key
13	Gland bolt
14	Gland spring

## Codes and Standards

ANSI B16.34  
ANSI B16.5  
ANSI B16.10  
ANSI B31.1  
ANSI B31.3  
ASME VIII Div. 1  
API 6D  
MSS-SP-61

## Materials

Carbon steel  
Stainless steel  
Hastelloy  
Incoloy  
5 chrome  
9 chrome  
Monel  
Alloy 20  
Ferallium  
Inconel  
Low alloy steel

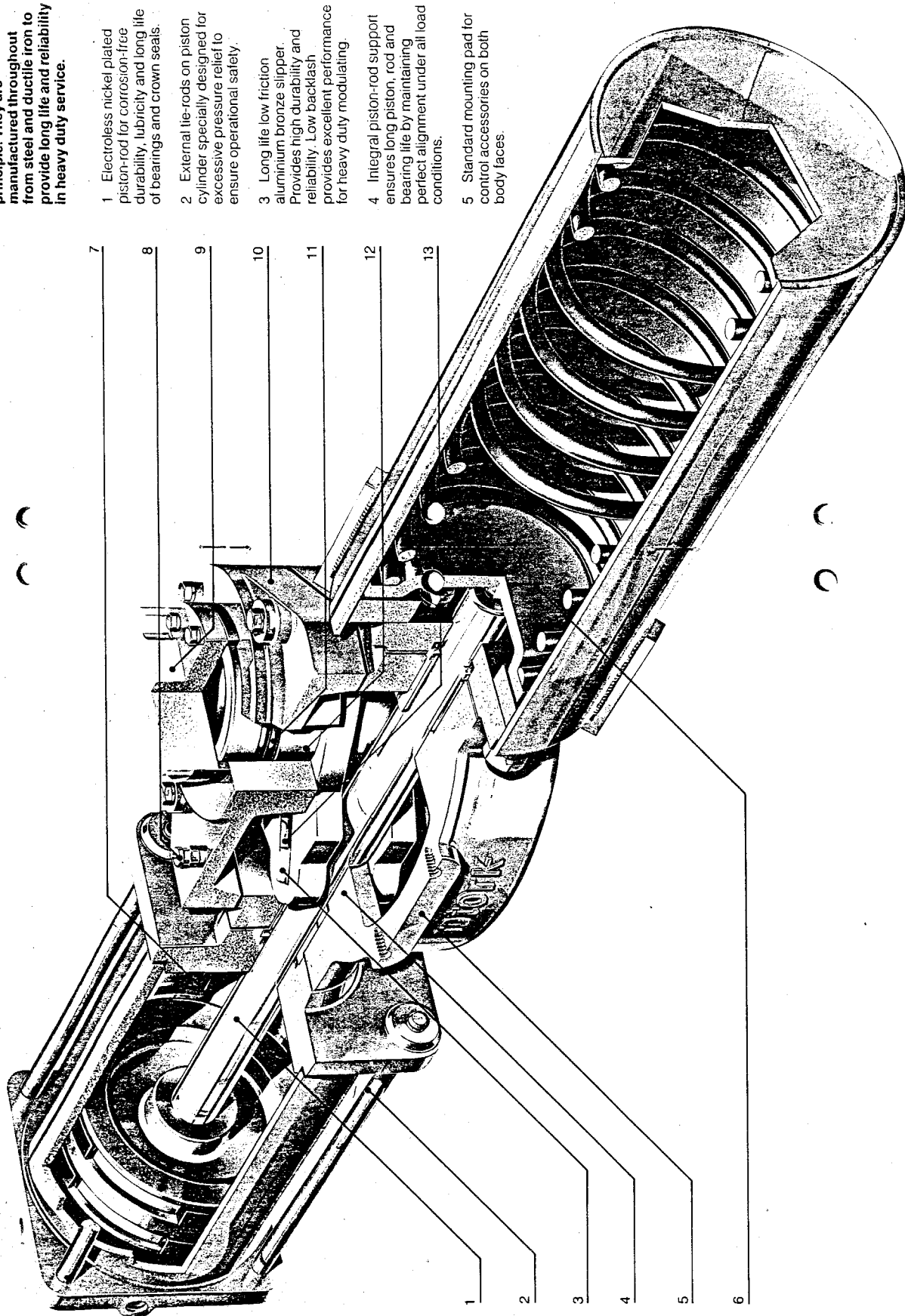
## Coatings (ball, seat, stem)

Chrome carbide  
Tungsten carbide  
Stellite  
Diffusion types



## 'p' Range pneumatic actuators

All 'p' Range actuators are of rugged modular construction, using the proven scotch yoke principle. They are manufactured throughout from steel and ductile iron to provide long life and reliability in heavy duty service.



- 1 Electroless nickel plated piston-rod for corrosion-free durability, lubricity and long life of bearings and crown seals.
- 2 External tie-rods on piston cylinder specially designed for excessive pressure relief to ensure operational safety.
- 3 Long life low friction aluminum bronze slipper. Provides high durability and reliability. Low backlash provides excellent performance for heavy duty modulating.
- 4 Integral piston-rod support ensures long piston, rod and bearing life by maintaining perfect alignment under all load conditions.
- 5 Standard mounting pad for control accessories on both body faces.

- 6 Inherently safe spring-return module with spring permanently contained in its factory welded module. Patent safety fastening ensures containment of spring forces before removal of module. US Patent No. 4 350 081.

- 7 Honed, electroless nickel plated, and polished cylinder walls provide maximum corrosion protection and lubricity for long life piston sealing and operational reliability.

- 8 The spring-loaded relief valve on the body allows for minor pressure variation while maintaining environmental and oil sealing.

- 9 Easily visible local position indicator, also operates limit switches and other accessories.

- 10 Removable cover for ease of inspection with specially long retaining bolts stressed to relieve excessive body pressure.

- 11 Exclusive Rotork double 'O' ring sealing gives proven protection against leakage in oil-filled service.

- 12 Phosphate and molybdenum disulfide coated torque plug bearings are combined with weather protection seals for maximum environmental protection of bearing surfaces regardless of choice of center body lubricant.

- 13 Precision machined torque-plug slots, phosphate and molybdenum disulfide coated

## Appendix C: Main Pressure Regulator

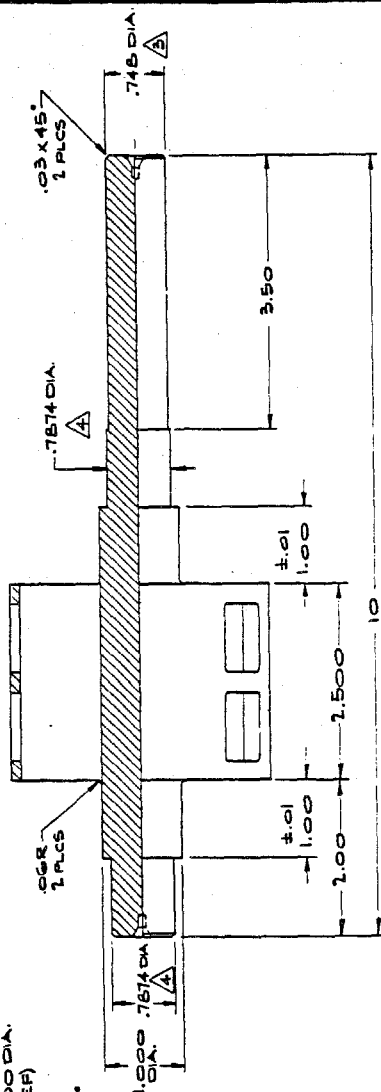
This appendix describes the main pressure regulator in greater detail. The information provided consists of:

- Engineering drawings of valve.
- Drawing of and device data sheets for the COMPUMOTOR KH-740 servo-motor and drive unit.



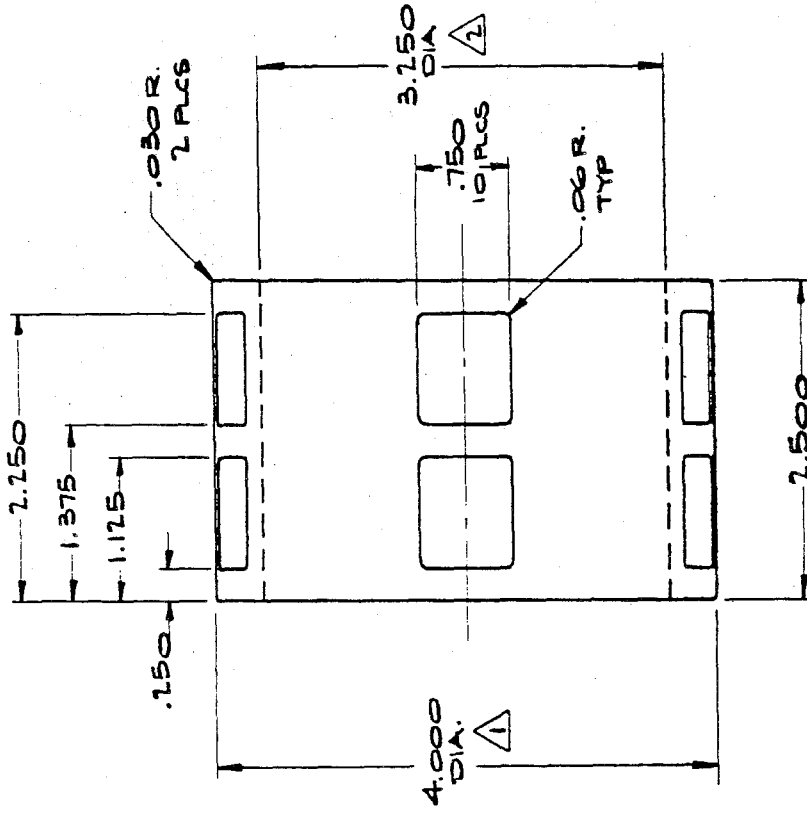
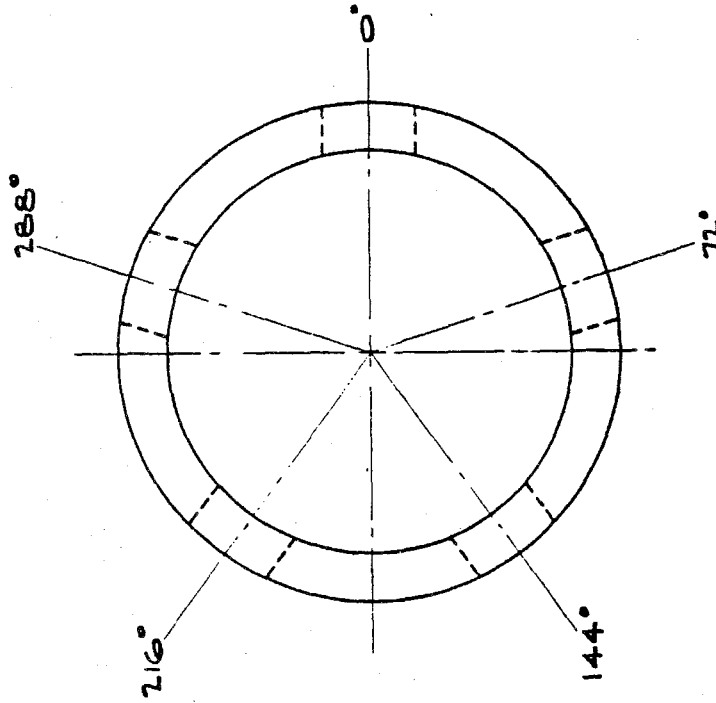
VALVE HOUSING





**NOTES: 1. REMOVE ALL BURRS AND SHARP EDGES.**

[illegible]



NOTES:  $\Delta$  .004 PRESS FIT IN HOUSING  
 $\Delta$  .004 CLEARANCE ON ROTATING CYLINDER

REV	PART NO	DESCRIPTION	MATERIAL	HEAT TREAT	ITEM
1	17-4 PH S.S.	SCALE FULLY	CALIFORNIA INSTITUTE OF TECHNOLOGY	TO COND.	
2	DATE	TITLE		H3922	
3	W.O.	FIXED CYLINDER			
4	DRAWN BY				
5	CHECKED				
6	NEXT ASSY				







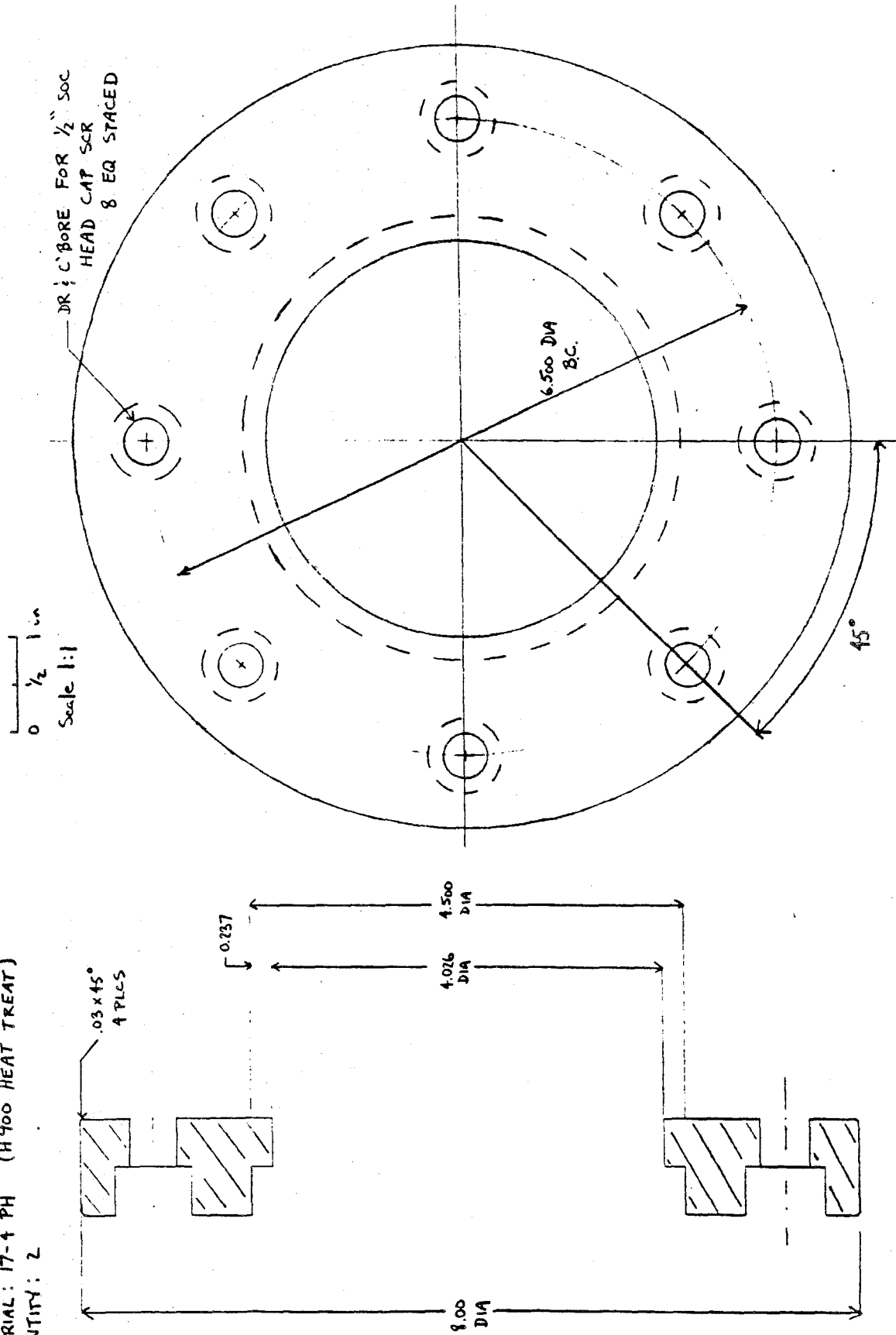




# THROTTLING VALVE INLET AND OUTLET FLANGES

03/02/88

MATERIAL: 17-4 PH (H900 HEAT TREAT)  
 QUANTITY: 2



## \* MRC Single-Row Deep-Groove Conrad Bearings—Type S

The MRC conrad bearing is a single-row radial deep-groove bearing with no filling notches. Assembly of the balls is made by eccentrically displacing the inner and outer rings, followed by a slight elastic distortion of the outer ring for the assembly of the last ball.

### Internal Clearance

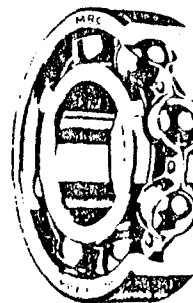
Conrad bearings are supplied with "loose" internal clearance unless otherwise specified. Loose clearance is commonly used for applications: (a) requiring a heavy press fit; (b) where the bearing must tolerate some misalignment; (c) where a significant temperature differential exists between the inner and outer rings; (d) where thrust load is heavier than normal. Other degrees of internal clearance can be furnished for special requirements.

### Common Parts

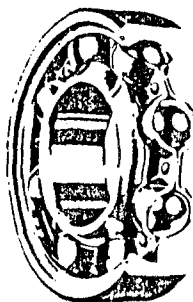
Many Type S bearings are made with common parts which are identified by the closure grooves on both inner and outer rings. This permits greater flexibility in providing bearings with seals and/or shields.

### Shields, Seals, Snap Rings

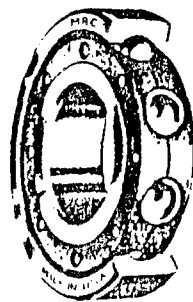
The bearings are available in many sizes with shields, seals or snap-rings, or a combination of these. Refer to the dimension pages for shielded, sealed and snap-ring bearings on which we are tooled. Where not shown they can be furnished on quantity orders. Marking may appear on the face or the outside diameter.



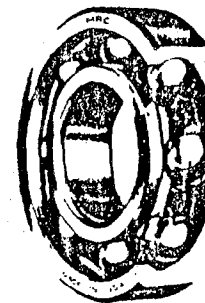
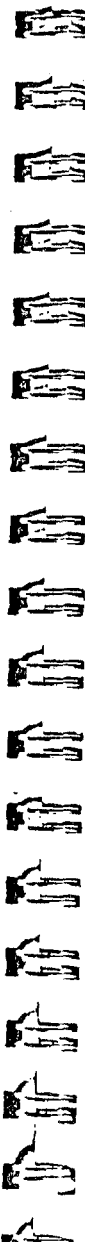
With Pressed Steel Cage



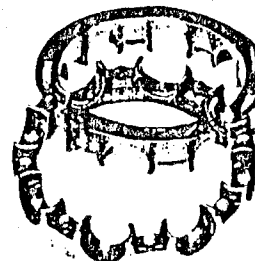
Common Parts Type Inner and Outer Rings



With Phenolic Composition Cage (Check availability)



With One-Piece Molded Nylon Snap-On Cage



Molded Retainers Showing Ball Pockets and Retainer Back

### Ball Cages

This type of bearing is supplied with either a pressed steel cage or a one-piece molded snap-on cage as standard, however, for special requirements, it can be supplied with a two-piece riveted machined cage of phenolic composition or bronze material.

### Where Recommended

The Type S conrad bearing is recommended for the majority of applications where a single-row bearing would normally be used, provided it has an adequate safety factor under the load conditions imposed. It has the ability to take equal thrust in either direction.

For load comparisons with other standard bearing types, see page 10.

MRC BRG. NOS.	SERIES	BORES*	Pages
R-2 thru R-24	Small Inch Size	1/8" thru 1"	14
34 thru 39	Extra Small	4 thru 9	15
1900-S thru 1940-S	Extremely Light	10 thru 200	16, 17
100-KS thru 136-KS	Extra Light	10 thru 180	18, 19
200-S thru 224-S	Light	10 thru 170	20, 21
300-S thru 322-S	Medium	10 thru 110	22, 23

\*MM except where otherwise indicated



\* Regulator uses type 204-S.

## SPECIFICATIONS

## System dependent:

DESCRIPTION	VALUE	UNITS
Repeatability	+/- 0.088	degrees, unloaded.
Accuracy	+/- 0.23	degrees, unloaded.
Relative Accuracy	+/- 0.088	degrees, any load.
Driver Operating Temperature	0 to +50	degrees Celsius.
Motor Operating Temperature	130	degrees Celsius, max.
Storage Temperature	-40 to +85	degrees Celsius.
Humidity	0 to 95	percent, non-condensing.

## Motor dependent:

(See torque speed curves)

DESCRIPTION	KH710	KH720	KH730	KH740	UNITS
Static Torque (cont.)	1034	2068	3399	4107	ounce-inches
Static Torque (peak)	2000	4000	6000	8000	ounce-inches
Top Speed	6000	2300	1450	1200	
revolutions/MINUTE					
Rotor Inertia	26.3	114.8	166.7	210.5	ounce-inches <sup>2</sup>
Maximum radial load					pounds
Motor Weight	18.7	36.3	47.3	58.3	pounds
Total Shipping Weight	65.7	83.3	94.3	105.3	pounds

## Physical Description

Drive Height: 16.75 INCHES (425mm)  
 Drive Width: 7.75 INCHES (197mm)  
 Drive Depth: 11.31 INCHES (287mm)

Drive Weight: 32 lbs ( 14.6kg)

## Environmental

Operating temperature: 32°F to 122°F (0°C to 50°C) With adequate air flow

Humidity: 0-95%, non-condensing.

## Common Specifications for the KS/KSX and KH/KHX series

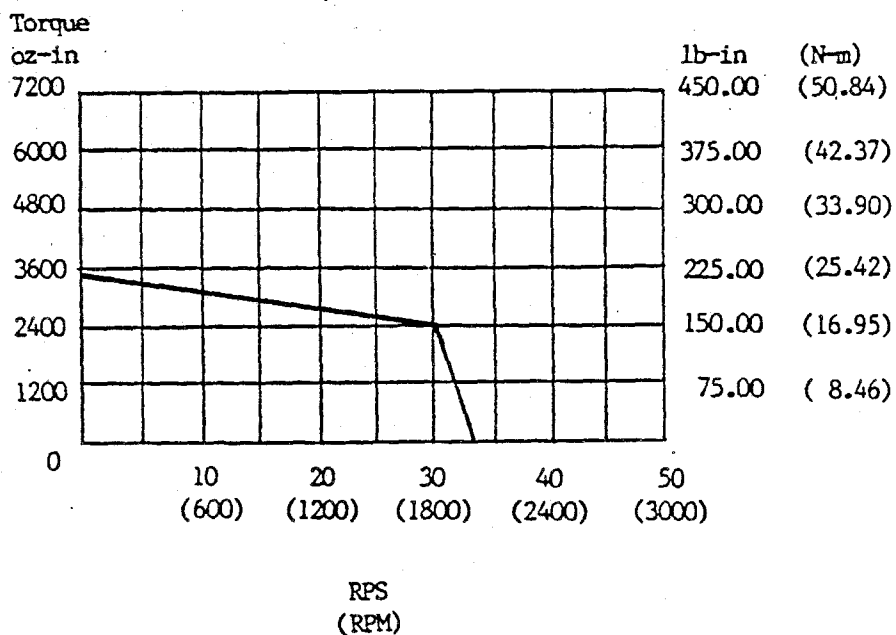
Parameter	Value																
<b>Performance:</b>																	
Repeatability	±5 arc min. (.088°) Unloaded-one revolution returning to start point from same direction																
Accuracy	±14 arc min. (0.23°) Unloaded-motor bearing and seal friction only																
Velocity accuracy	±.02% of set speed, average																
<b>Resolution:</b>																	
User Selectable over RS-232 C	1000-8192 steps/rev. KS 210, 220, 230, 240 1000-16384 steps/rev. KS 250, 260 1000-32768 steps/rev. KH (All Models)																
Factory Setting:	5000 steps/rev. (All Models)																
	<table><tr><th>KS/KSX</th><th>KH/KHX</th></tr><tr><td colspan="2"><b>Power:</b></td></tr><tr><td>Control and Motor</td><td>Control Motor</td></tr><tr><td>Volts: Nominal</td><td>120 VAC, 1 phase 240 VAC, 3 phase</td></tr><tr><td>Range</td><td>(100-130) (100-130) (100-252)</td></tr><tr><td>Frequency</td><td>50/60 Hz 50/60 Hz 50/60 Hz</td></tr><tr><td>Current</td><td>16 A max 1 A max 30 A max</td></tr><tr><td colspan="2">(Note: KH/KHX require both 120 VAC single phase and 240 VAC three phase power)</td></tr></table>	KS/KSX	KH/KHX	<b>Power:</b>		Control and Motor	Control Motor	Volts: Nominal	120 VAC, 1 phase 240 VAC, 3 phase	Range	(100-130) (100-130) (100-252)	Frequency	50/60 Hz 50/60 Hz 50/60 Hz	Current	16 A max 1 A max 30 A max	(Note: KH/KHX require both 120 VAC single phase and 240 VAC three phase power)	
KS/KSX	KH/KHX																
<b>Power:</b>																	
Control and Motor	Control Motor																
Volts: Nominal	120 VAC, 1 phase 240 VAC, 3 phase																
Range	(100-130) (100-130) (100-252)																
Frequency	50/60 Hz 50/60 Hz 50/60 Hz																
Current	16 A max 1 A max 30 A max																
(Note: KH/KHX require both 120 VAC single phase and 240 VAC three phase power)																	
<b>Inputs:</b> (Step, Direction Shutdown, CW & CCW Limits, Home Limit, Trigger 1, 2, 3)	Optically isolated 5-12 VDC 500 N. sec. minimum pulse width, step input only 20 mA maximum source current required																
<b>Outputs:</b> (Drive Fault, In Position, Programmable Outputs)	Optically isolated NPN transistor 3.0 mA minimum, 5 Volts Sink or Source																
<b>Interface RS-232C</b>																	
Baud	Fixed 9600																
Data Bits	8																
Stop Bits	1																
Parity	None																
<b>Environmental:</b>																	
Operating	32 to 104°F (0 to 40°C) ambient																
Driver	Maximum heatsink temperature is 150°F (65°C)																
<b>Motor</b>	32 to 104°F (0 to 40°F) ambient Maximum motor case temperature is 266°F (130°C)																
Storage	-40 to 185°F (-40 to 85°C)																
Humidity	0 to 95% Non-condensing																

APPENDIX C  
(Continued)

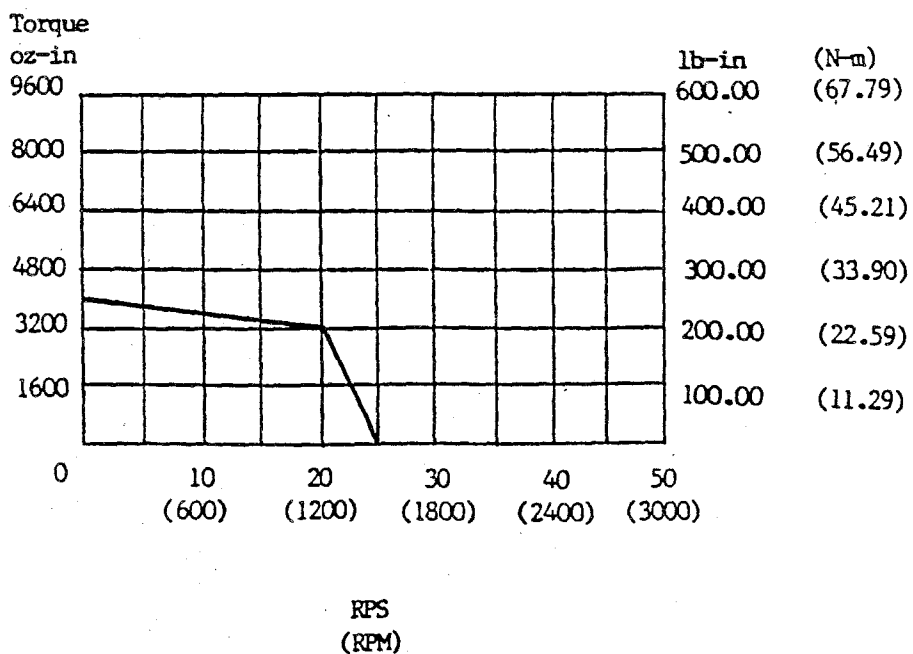
## TORQUE SPEED CURVES

KH MOTORS

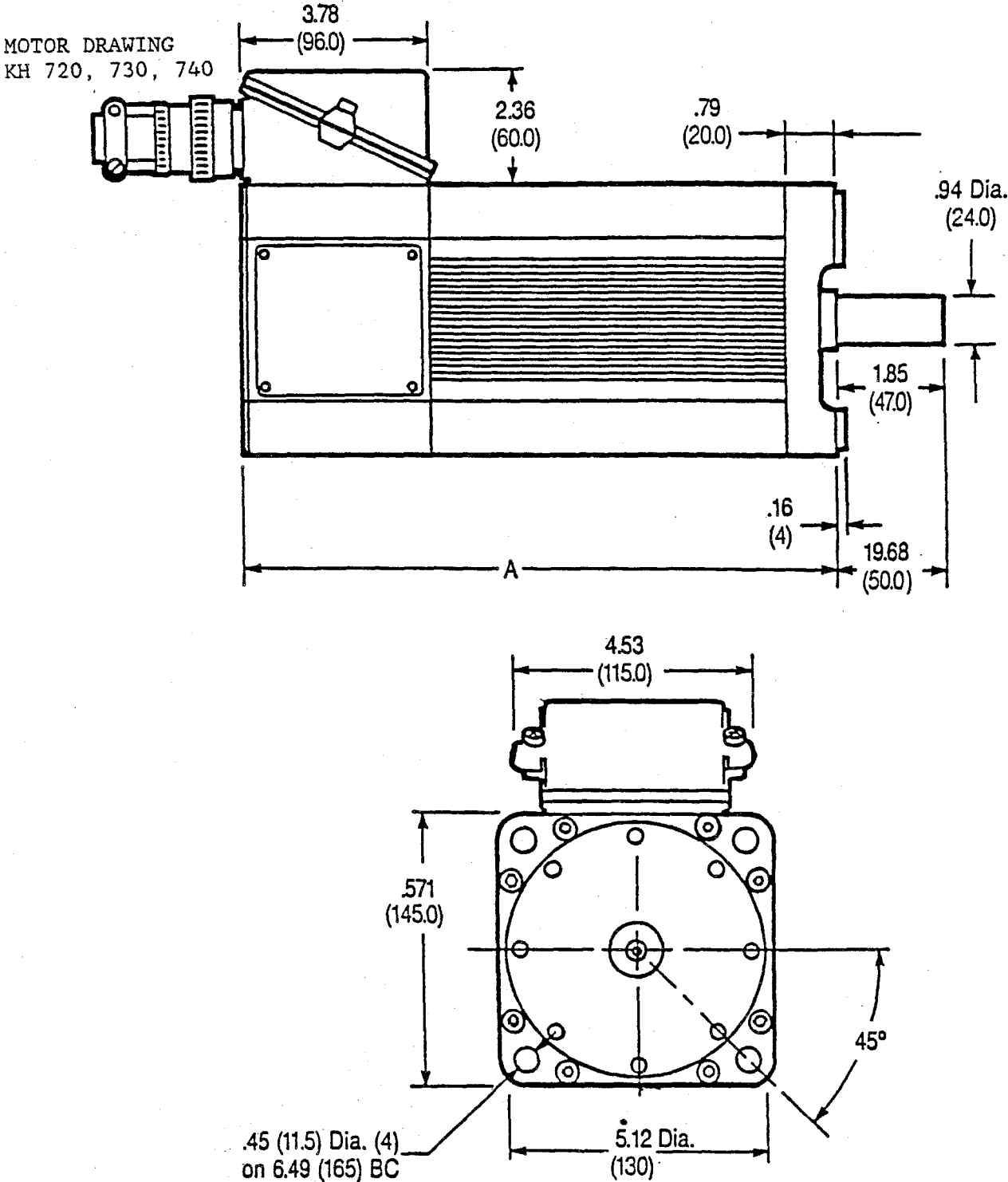
KH-730



KH-740



APPENDIX B  
(Continued)





## Appendix D: Test Section

This appendix describes the test section in greater detail. The information provided consists of:

- General information (this page).
- Engineering drawings of the test section components, including nozzle contours and the test section/shower tunnel mating flange.
- Data sheets on the pressure transducers.
- Calculation of the design pressure loading.

The basic test section frame is constructed from 3.5 inch thick 6061 – T6 aluminum plate. It is a bolted assembly using 3/4" – 10 bolts for fastening and 3/4 inch tapered dowel pins for alignment. The internal frame (end plates, top and bottom plates) is, for most practical purposes, permanently bolted together. Sealing between these plates is provided by silicon gasket material which set after the plates were connected. Sealing between the side plates and this internal frame is provided by viton o-rings. This o-ring groove is not shown on any of the drawings.

The plate calculation to follow demonstrates that the test section is essentially designed for 1500 psi, which will accomodate the maximum  $H_2/NO$  Reactant Tank pressure in the event of a regulator failure.

The nozzle blocks were machined out of 6 inch thick 2219 – T8 aluminum plate. The basic shape was roughed out with saw cuts. The final machining was done on a numerically controlled mill with a final accuracy of approximately 0.002 inch. Imperfect smoothing of the machined contour required some sanding (by hand) to achieve the final surface finish.

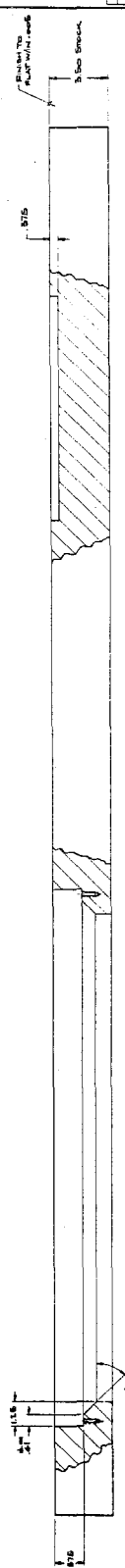
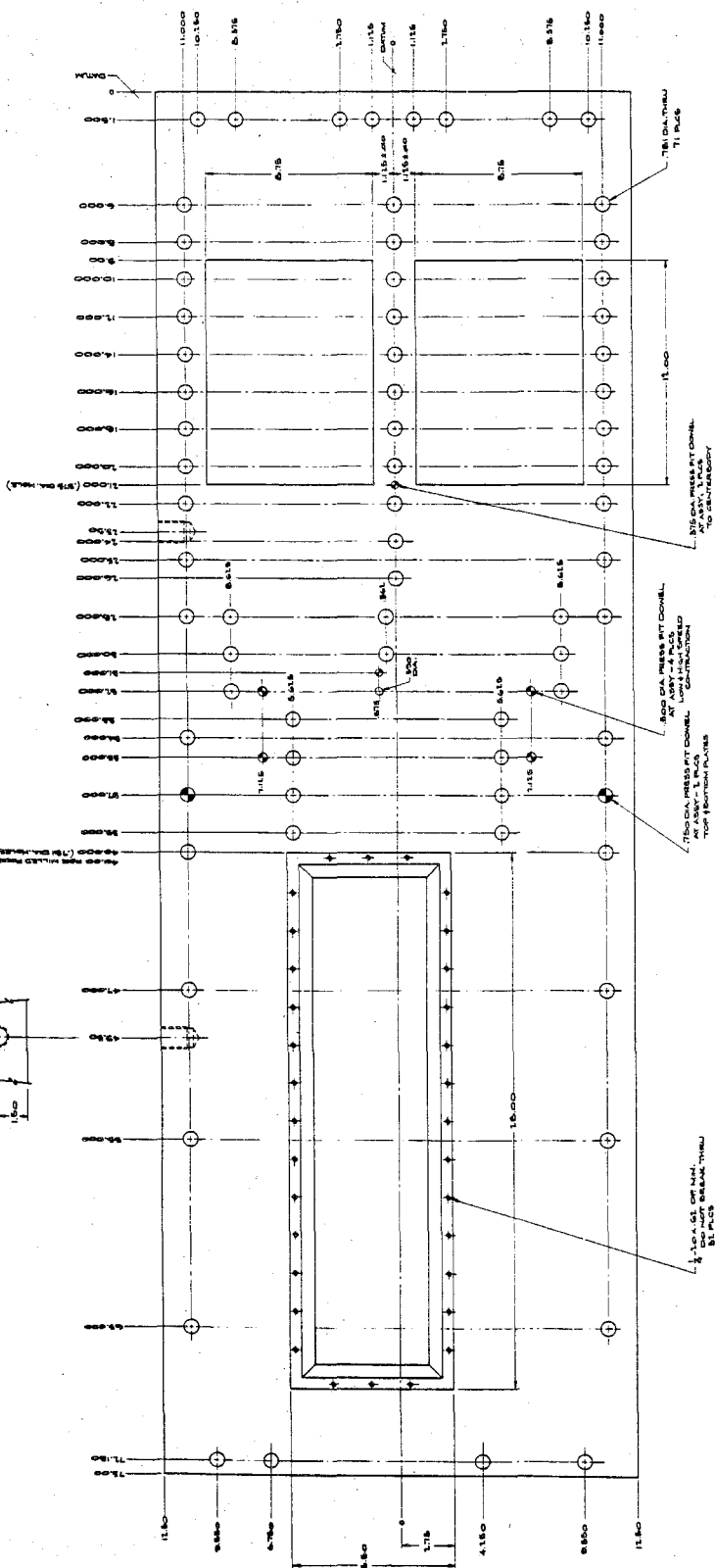
The windows were constructed by Sydor Optics Co. from BK7 optical glass. The design specifications were:

- $5\lambda$  flatness over the entire surface.
- 25 angstrom rms surface polish.
- 1 arcminute parallelism.

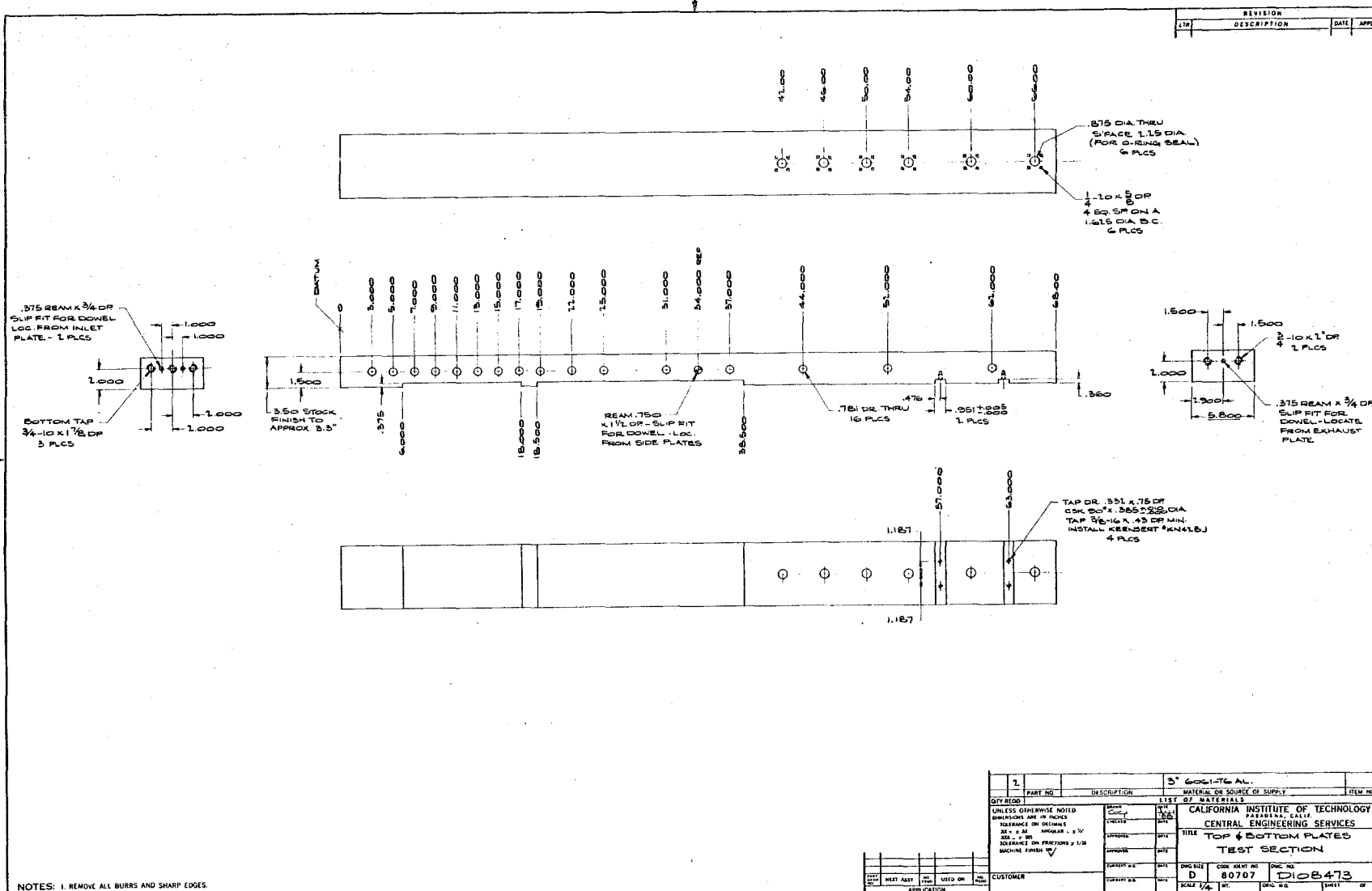
The bevelled edgework allows the windows to be clamped into the side plates with the frames shown in the drawing. This method of clamping was designed to avoid any acute internal angles that would lead to stress concentration and subsequent fatigue and cracking.

The pyrex plates clamped over the optical windows serve as protection from the fluorine gas. The idea is that the pyrex plates can be cheaply replaced when the chemical etching has become intolerable, whereas we simply cannot afford to replace the optical windows. The pyrex is polished to an unknown specification.

The small flanges on the top and bottom of the test section allow for access to the interior of test section, either for gas flows, electrical signals or optical diagnostics. One such flange on the top and bottom is connected to the system purge network to allow nitrogen gas to be pumped through the test section. Four more flanges have a large number of electrical wires and pressure tubes epoxied into them, to make feedthroughs for the pressure and temperature transducer signals. The remaining flanges are currently spares.

[illegible]

NOTES: 1. REMOVE ALL BURLS AND SHARP EDGES.



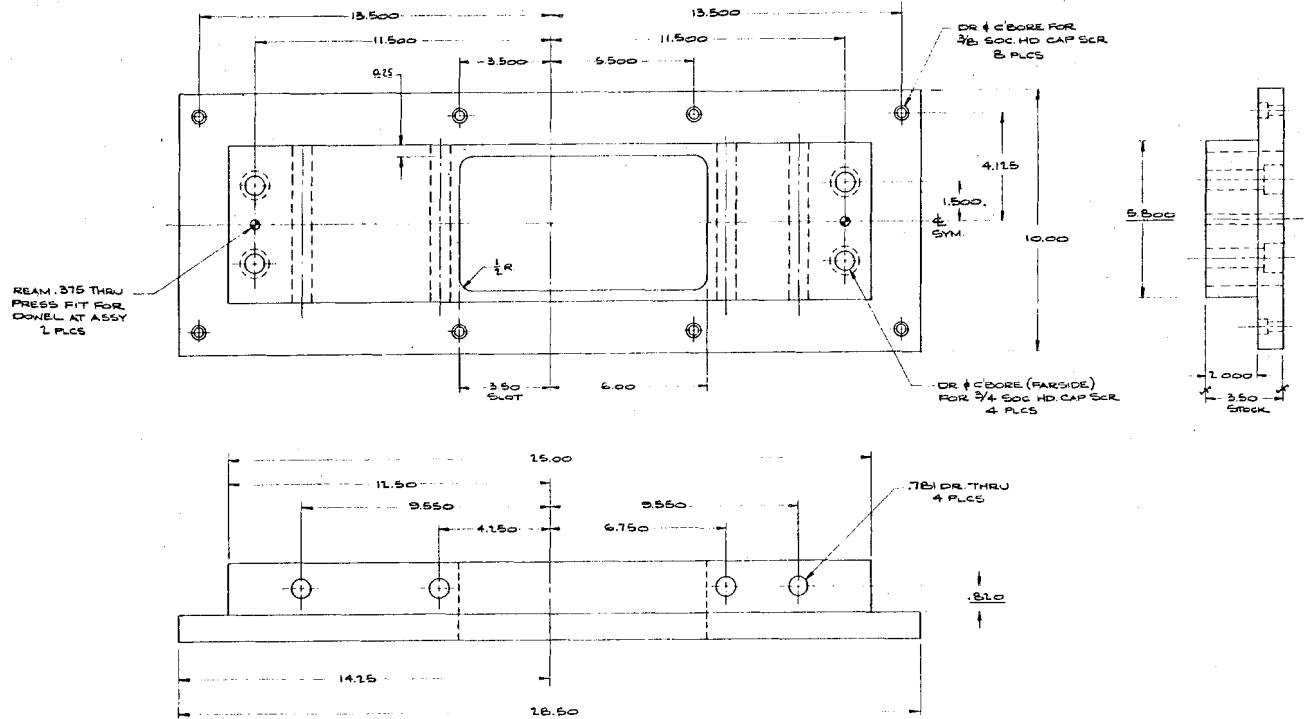
**NOTES:** 1. REMOVE ALL BURRS AND SHARP EDGES

MAILING LIST: \$45000 (11) 100-0

[illegible]



REVISION			
LIN	DESCRIPTION	DATE	APPD



NOTES: 1. REMOVE ALL BURRS AND SHARP EDGES

PART NO		DESCRIPTION		3" RE GOO-TAL.		ITEM NO	
QTY REQD		MATERIAL OR SOURCE OF SUPPLY		LIST OF MATERIALS		ITEM NO	
UNLESS OTHERWISE NOTED DIMENSIONS ARE IN INCHES TOLERANCES ON DIMENSIONS ALL - ± .01 ANGULAR - ± .1° HOLE - ± .005 TOLERANCE ON FRACTIONS ± .015 MACHINE FINISH UNLESS NOTED		CALIFORNIA INSTITUTE OF TECHNOLOGY PASADENA, CALIF. CENTRAL ENGINEERING SERVICES		TITLE EXHAUST PLATE TEST SECTION		D 80707 D10B475	
DATE		DRAWN BY		CHECKED BY		SCALE 1/1	
APPD		CUST		DATE		SHEET 1 OF 1	

D10B475

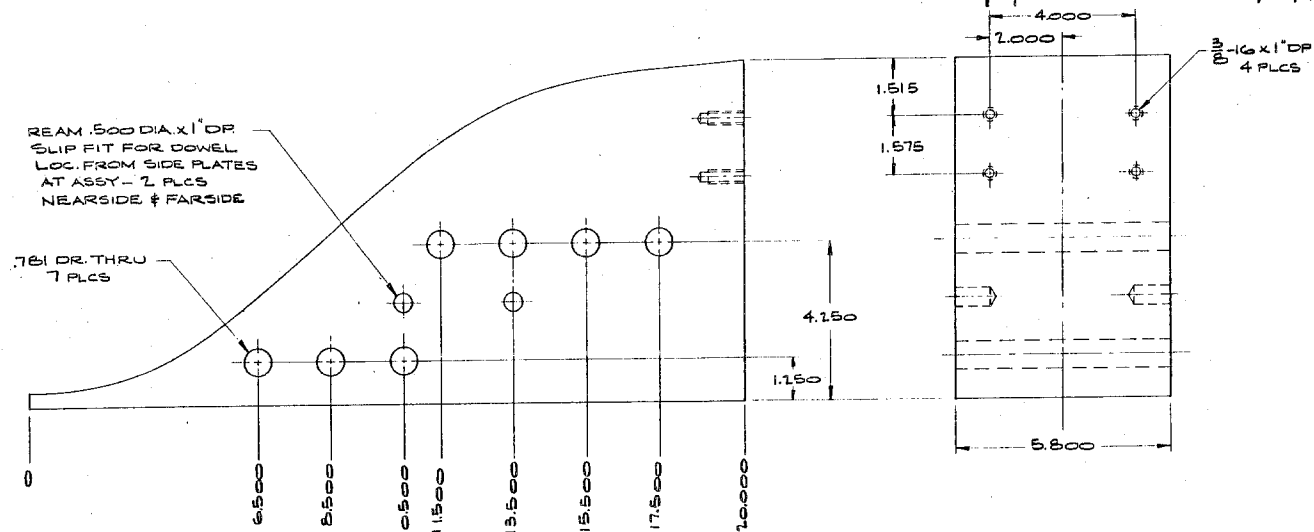






REAM .500 DIA X 1" DP  
SLIP FIT FOR DOWEL  
LOC. FROM SIDE PLATES  
AT ASSY - 2 PLCS  
NEAR SIDE & FAR SIDE

.751 DR. THRU  
7 PLCS



NOTES: 1. REMOVE ALL BURRS AND SHARP EDGES.

DIETRICH-PORT CLEARPRINT 1030 B

PART NO.	NEXT ASSY	NO. REQD	USED ON	NO. REQD

APPLICATION

1		PART NO.		DESCRIPTION		6061-T6 AL.		MATERIAL OR SOURCE OF SUPPLY		UNIT WT.		ITEM NO.	
QTY REQD.		APPROVED		CHECKED		DATE		DATE		DATE		DATE	
UNLESS OTHERWISE NOTED DIMENSIONS ARE IN INCHES TOLERANCE ON DECIMALS XX = ± .03 ANGULAR = ± 1° XXX = ± .005 TOLERANCE ON FRACTIONS ± 1/16 MACHINE FINISH ✓		APPROVED		CHECKED		DATE		DATE		DATE		DATE	
CURRENT W.O.		DATE		DATE		DATE		DATE		DATE		DATE	
CURRENT W.O.		DATE		DATE		DATE		DATE		DATE		DATE	
CUSTOMER		DWG. NO.		CODE IDENT NO.		DWG. NO.		SCALE 1/2		WT.		SHEET OF	
		C		80707		C108478							

C108478

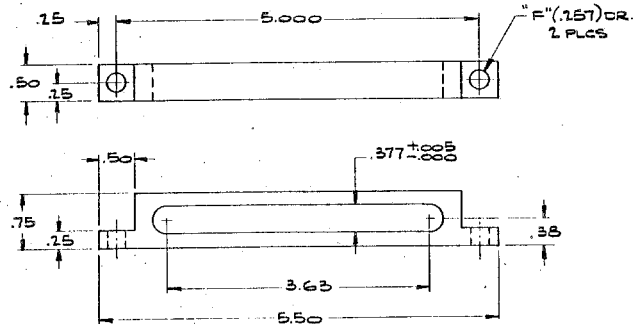




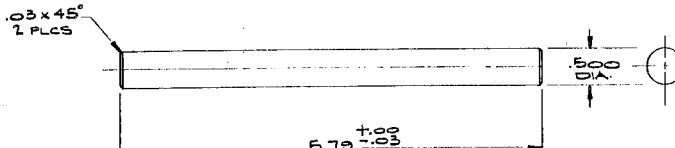


DIERICH POST CLEARPRINT 1929

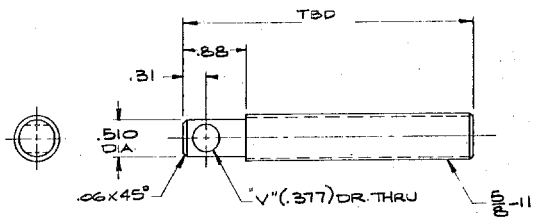
POSTERIOR-POST CLEARPRINT 1020-B



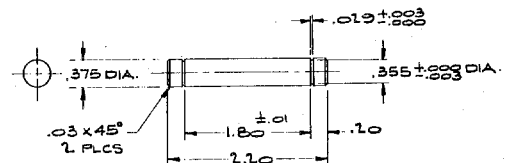
① AXLE TAB



② SIDEWALL AXLE



③, ④ ADJUST. SCREW



⑤ AXLE

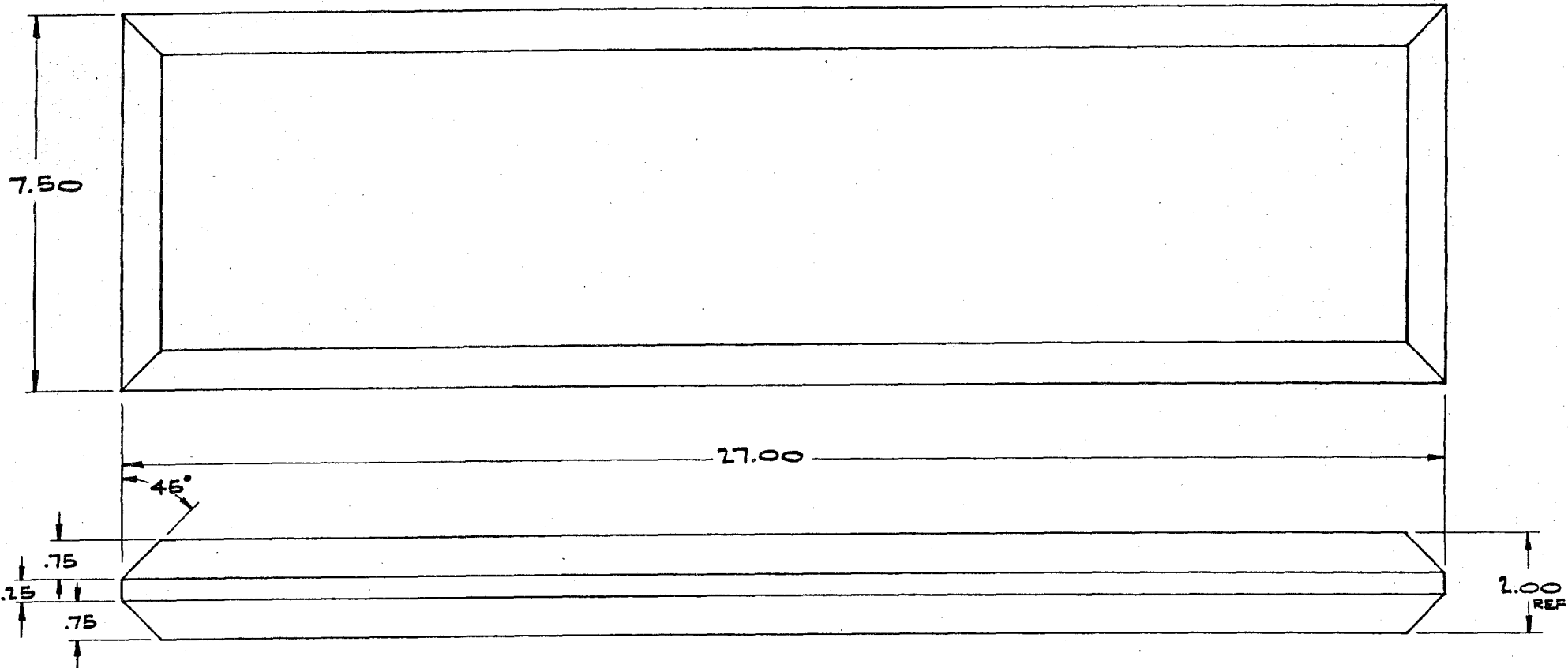
2. HEAT TREAT ITEMS 2 & 5 TO COND. H300  
NOTES: 1. REMOVE ALL BURRS AND SHARP EDGES.

2	AXLE	.375 DIA. PREC. GRND 17-4 PH	5		
1	ADJUST. SCREW	316 S.S. THRD ROD	4		
1	ADJUST. SCREW	316 S.S. THRD ROD	3		
1	SIDEWALL AXLE	.500 DIA. PREC. GRND 17-4 PH	2		
4	AXLE TAB	316 S.S.	1		
PART NO.		DESCRIPTION	MATERIAL OR SOURCE OF SUPPLY	UNIT WT	ITEM NO.
QTY REQ					
UNLESS OTHERWISE NOTED DIMENSIONS ARE IN INCHES TOLERANCE ON DECIMALS XX = ± .01 ANGULAR ± 1° XXX = ± .005 TOLERANCE ON FRACTIONS ± 1/16 MACHINE FINISH UNLESS OTHERWISE NOTED					
DRAWN CRY		DATE 7/88	LIST OF MATERIALS		
CHECKED		DATE	CALIFORNIA INSTITUTE OF TECHNOLOGY PASADENA, CALIF. CENTRAL ENGINEERING SERVICES		
APPROVED		DATE	TITLE DETAILS -		
APPROVED		DATE	SIDEWALL ADJUSTMENT MECH		
			TEST SECTION		
CURRENT W.D.		DATE	OWG SIZE C	CODE IDENT NO 80707	OWG NO. C108484
CURRENT W.D.		DATE	SCALE FULL WT. ORG. W.D. SHEET OF		
CUSTOMER					

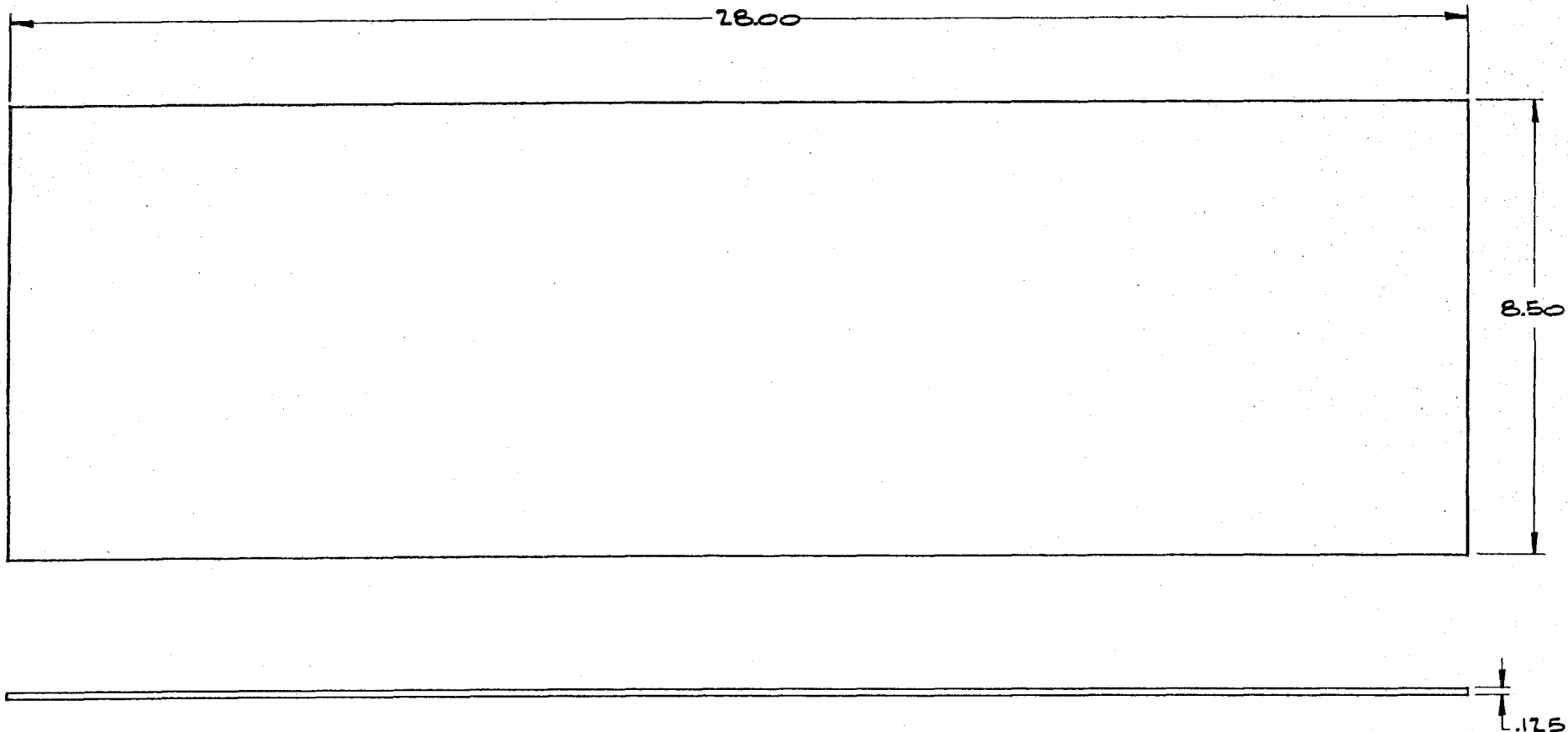
C108484

OUTER RIM POST CLEARING 19308



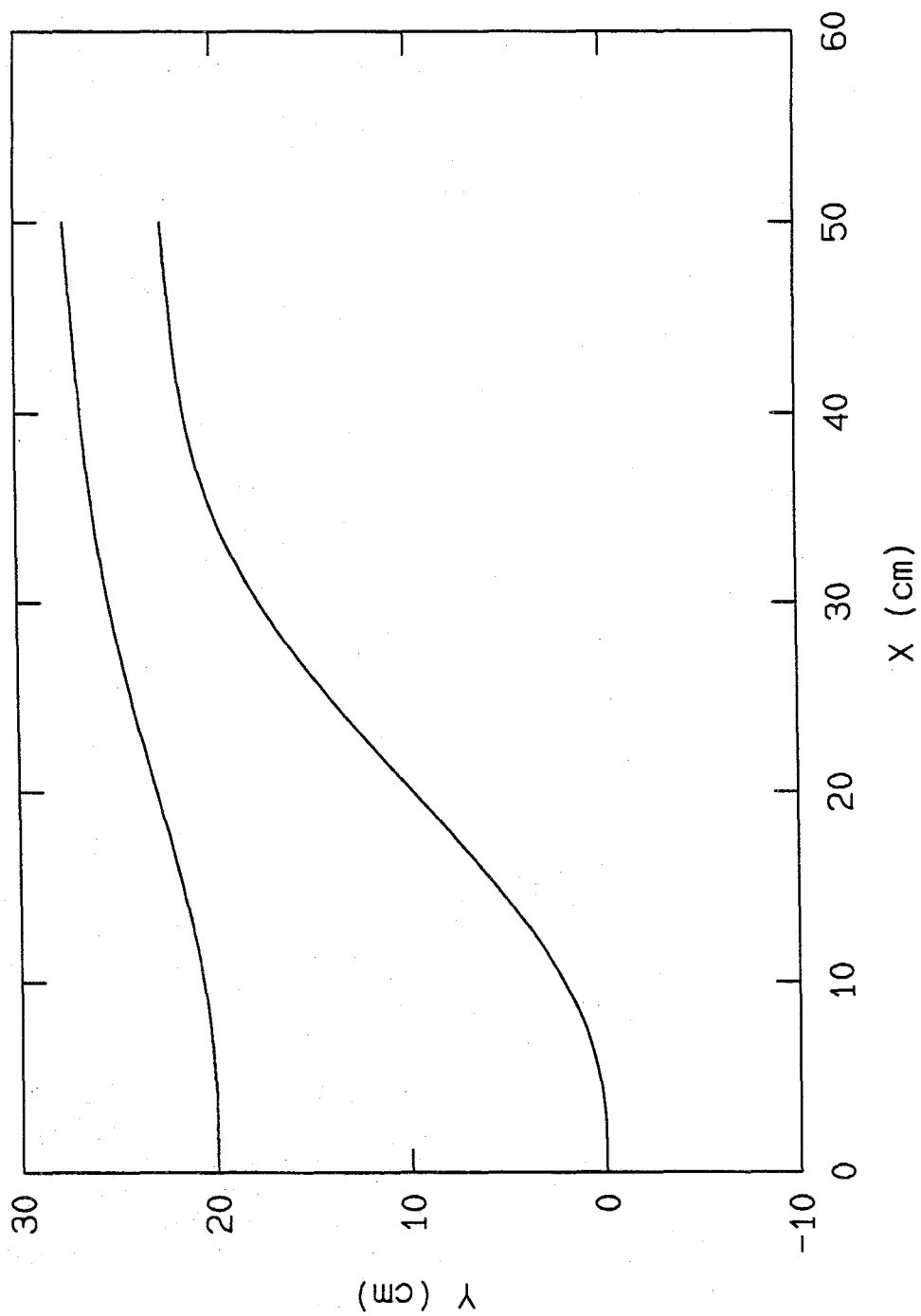


2			2" # GLASS		
REQ.	PART NO.	DESCRIPTION	MATERIAL	FINISH	ITEM
XX = $\pm$ .03 FRACTIONS $\pm$ 1/16		W.O.	CALIFORNIA INSTITUTE OF TECHNOLOGY		
XXX = $\pm$ .003 ANGULAR $\pm$ 1/2°		DATE	SCALE 1/2		
DRAWN BY GGP		JUL '88	TITLE WINDOW		DRAWING NO.
CHECKED			TEST SECTION		B108485
NEXT ASSY					CHG.

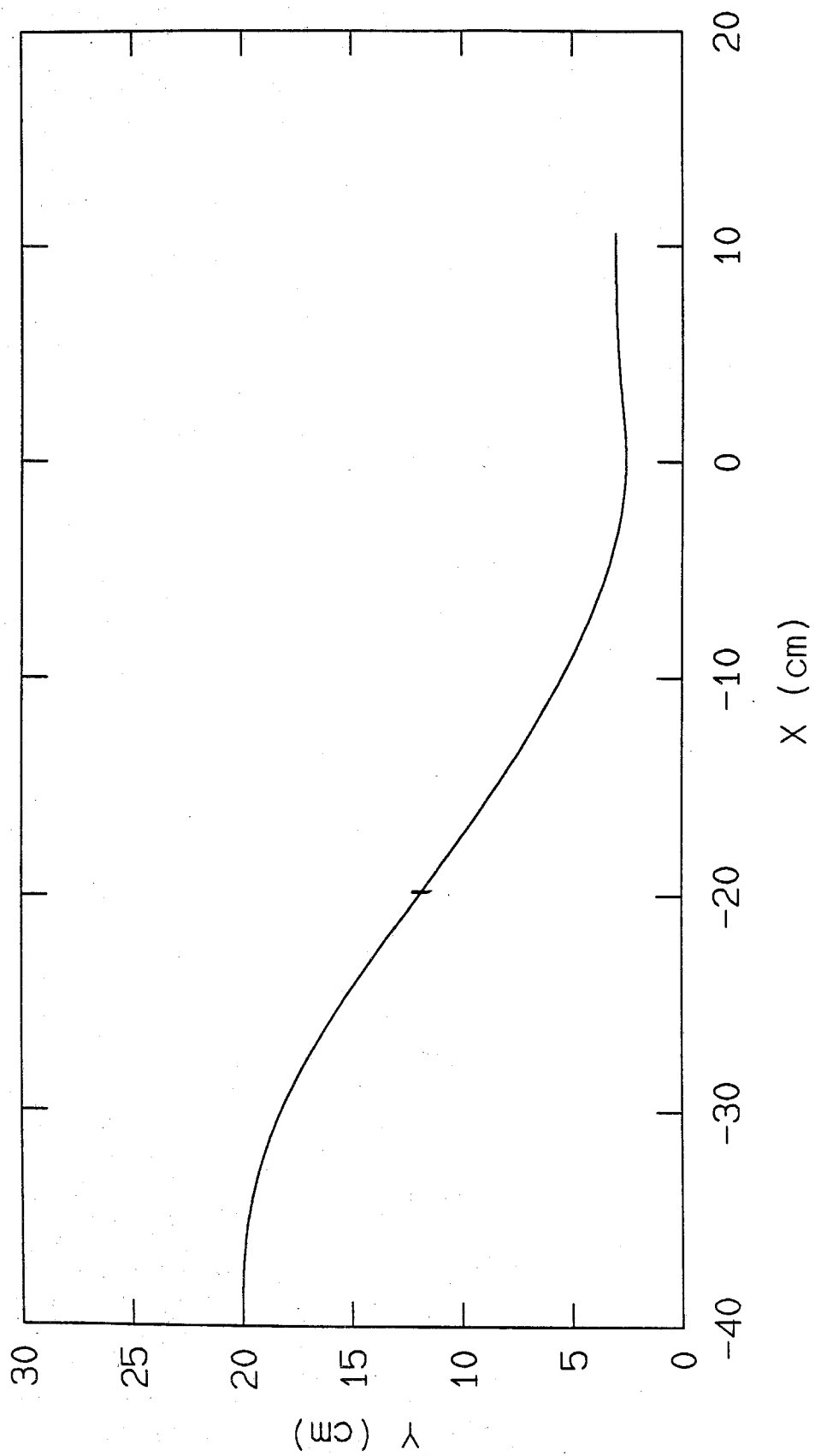


2			1/8 PYREX		
REQ.	PART NO.	DESCRIPTION	MATERIAL	FINISH	ITEM
XX = 1/2 82 FRACTIONS 1/16 XXX = 1/2 805 ANGULAR 1/16		W.O.	CALIFORNIA INSTITUTE OF TECHNOLOGY		
		DATE	SCALE 1/2		
DRAWN BY GEP		JULY 88	TITLE		DRAWING NO.
CHECKED			WINDOW COVER		8108486
NEXT ASSY			TEST SECTION		CHG.

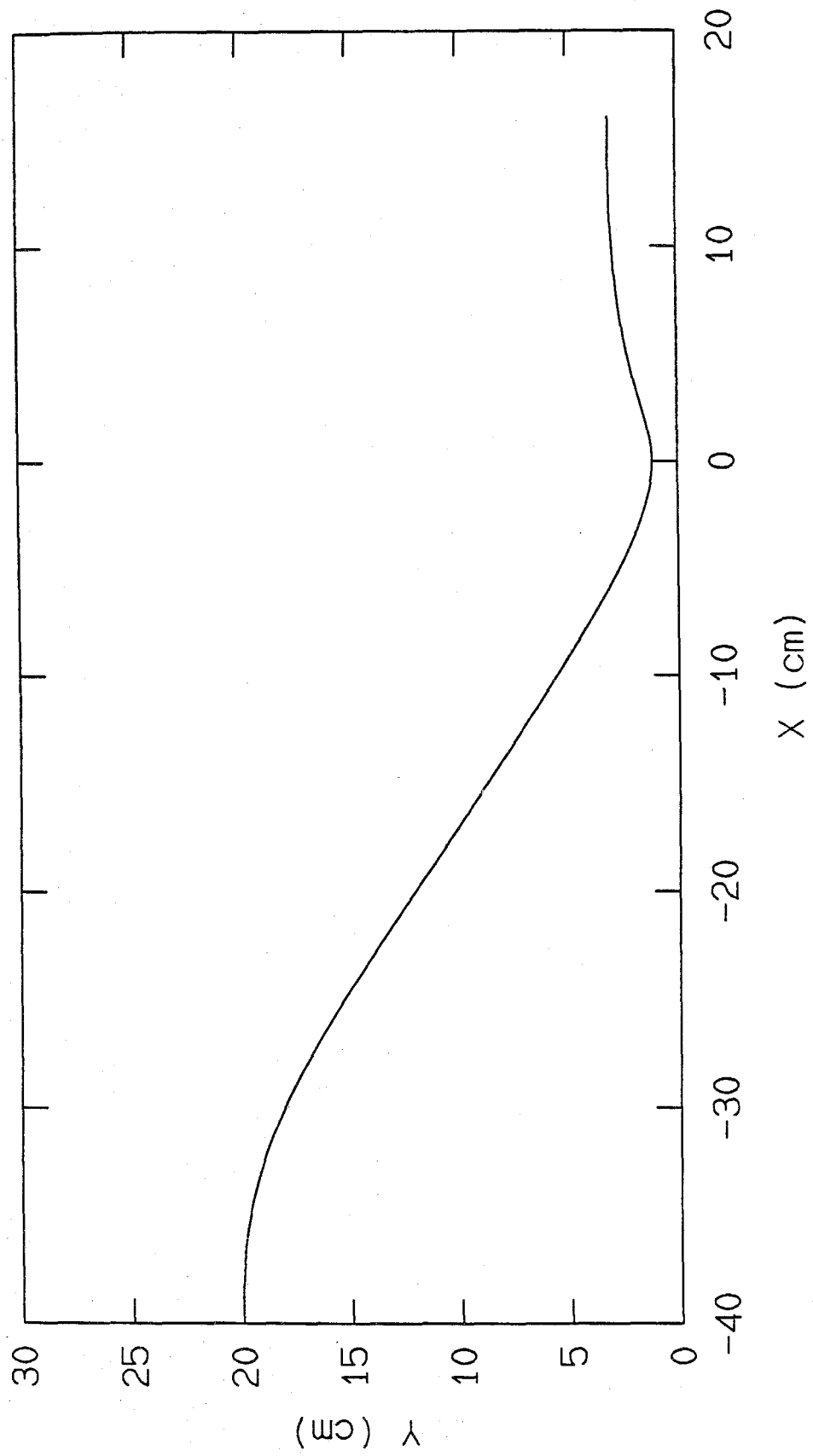
# CONTOURS FOR SUBSONIC CONTRACTION



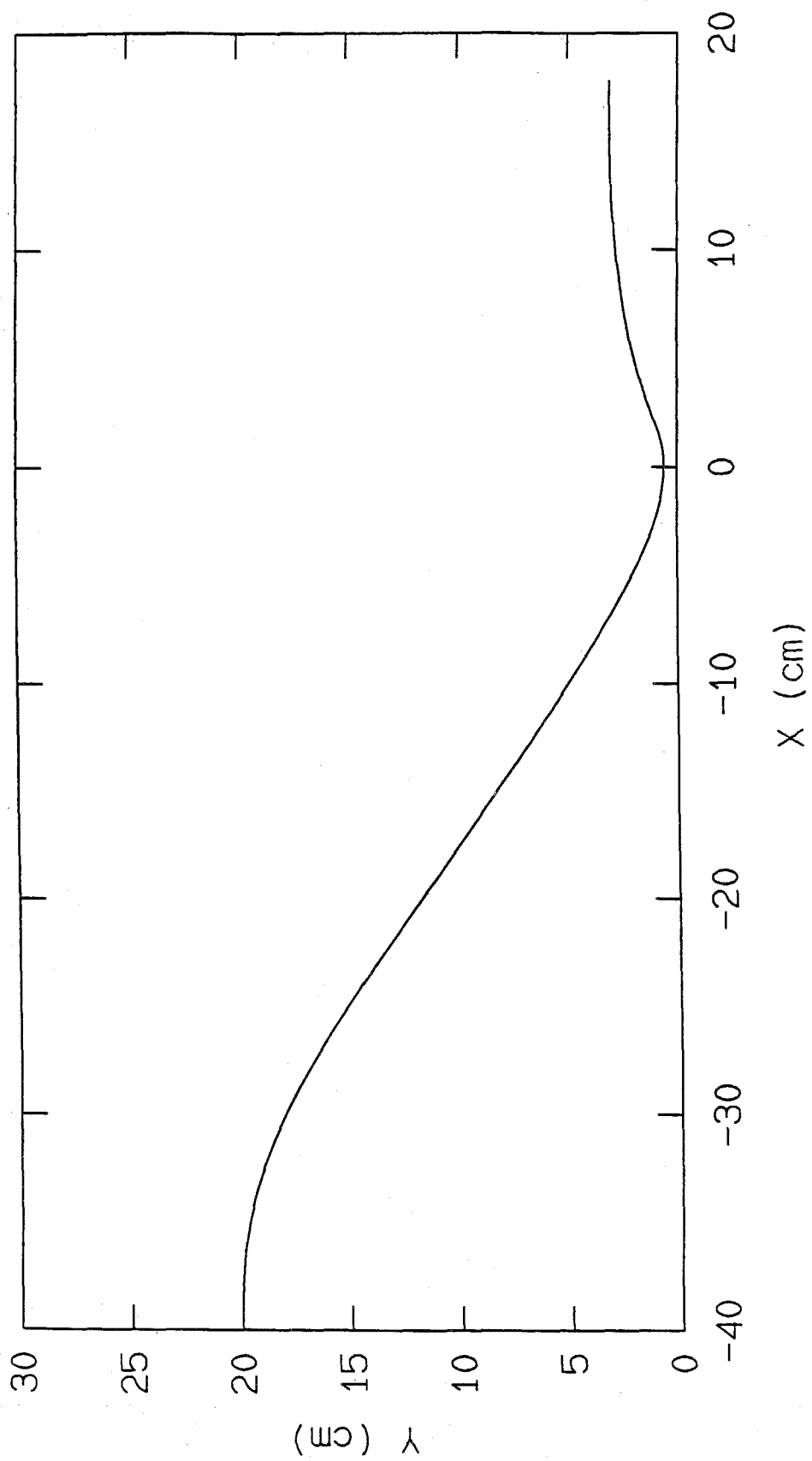
# SUPERSONIC CONTOUR FOR $M=1.5$



SUPERSONIC CONTOUR FOR  $M=2.5$



# SUPERSONIC CONTOUR FOR $M=3.2$

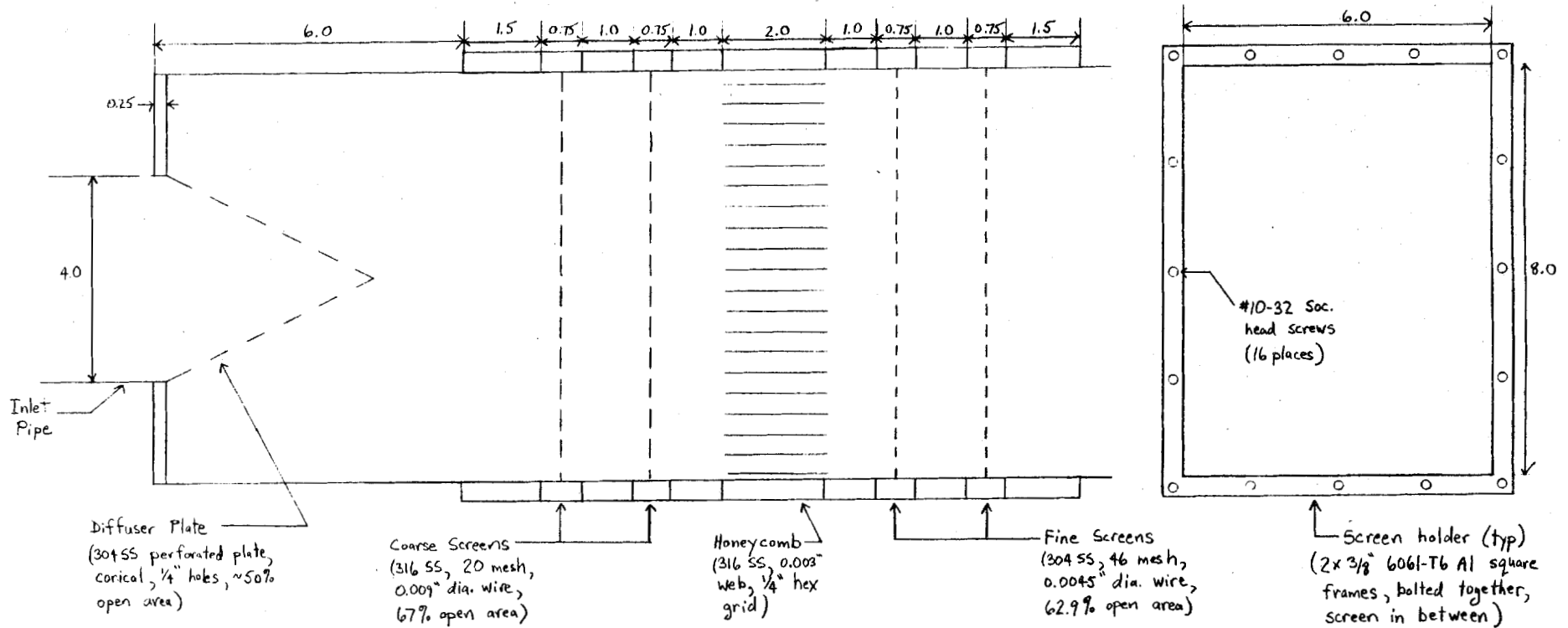


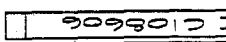
# DETAILS OF FLOW MANAGEMENT SYSTEM

0 1 2 inch  
Scale: 1/2

Note: Layout is the same for both low speed and high speed streams.

Drawn by: Jeff Hall  
Dated : 08/25/89





2 ASSEMBLIES REQD  
(1) R.H.  
(1) L.H.

VIEW B-B

**NOTES: 1. REMOVE ALL BURRS AND SHARP EDGES.**

[illegible]

**UNITED STATES POST OFFICE**





## MINIATURE SEMICONDUCTOR PRESSURE TRANSDUCER

### Type PDCR 200

**Excellent linearity and hysteresis**  
±0.2% BSL for all ranges to 1500 psi

**Flush mounting**

**Fast response**

**Excellent overpressure acceptance**  
≤ 3 times rated pressure

**Good thermal stability**  
±1% total error for 50° to 140°F

**High output**

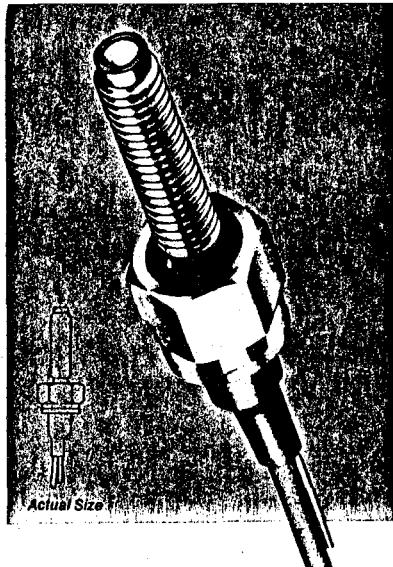
The PDCR 200 is a miniature flush mounting fast response pressure transducer which retains many of the excellent features of the larger more conventional pressure transducers from Druck. The silicon diaphragm used has a fully active integrated strain gauge bridge which is selected for high accuracy and good stability. They are compatible with most fluids and easy to install with an 'O' ring seal.

For differential and absolute use, a reference pressure connector is fitted as standard and screens can be provided for applications where erosion by high velocity particles is a problem.

**Operating pressure ranges**  
15, 30, 50, 100, 200, 500, 900 and 1500 psi gauge or differential.  
Other pressure units can be specified, e.g. kPa.  
Other ranges are available on request.  
For absolute pressures vacuum can be pumped on the reference.

**Overpressure**  
The rated pressure can be exceeded by the following multiples causing negligible calibration change:  
Positive side:  
3 x for all ranges.  
Reference side:  
2 x for 15 and 30 psi ranges.  
The transducer can be used in a bi-directional differential mode up to ±15 psi.

**Positive pressure media**  
Fluids compatible with quartz and titanium.



**Reference pressure media**  
Dry, non-corrosive, non-conducting gases.

**Transduction principle**  
Integrated silicon strain gauge bridge.

**Excitation voltage**  
10V d.c. or a.c. maximum and regulated @ 15mA maximum.

**Output voltage/natural frequency**

Pressure Range psi	Output Nominal mV	Natural Frequency kHz
15	150	75
30	150	100
50	150	130
100	150	180
200	150	290
500	150	410
900	150	580
1500	150	760

Outputs quoted are for standard linearity and overload.  
Higher outputs are possible giving proportional improvements in temperature stability.

**Output impedance**  
1000 ohms nominal.

**Load impedance**  
Greater than 100K ohms for quoted performance.  
For lower load impedances, please specify.

**Resolution**  
Infinite.  
Combined non-linearity and hysteresis  
±0.2% BSL for all ranges.  
Better available on request. Please refer to manufacturer.

**Zero offset**  
<10mV standard.

**Operating temperature range**  
-5° to +250°F standard (-20° to +120°C).  
This temperature range can be extended.

**Temperature effects**  
±1% total error band 50° to 140°F (10° to 60°C).  
For special applications it is possible to give improved temperature compensation over a 90°F (50°C) band within the operating temperature range.  
Please refer to manufacturer.

**Acceleration sensitivity**  
0.002% FSO/g for 15 psi decreasing to 0.0001% FSO/g for 1500 psi.

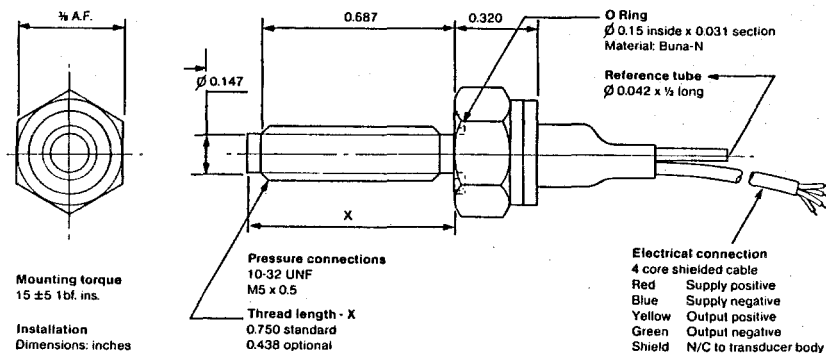
**Mechanical shock**  
1000g for 1ms in each of three mutually perpendicular axes will not affect calibration.

**Weight**  
0.4 oz. nominal

**Electrical connection**  
3 ft. teflon cable supplied.  
Longer lengths available on request.

**Options available**  
Alternative thread lengths - see installation.  
Protective screen.

**Ordering information**  
Please state the following:  
(1) Type number  
(2) Pressure range  
(3) Gauge or differential  
(4) Temperature range  
(5) Pressure connection  
(6) Pressure media  
For non-standard requirements please specify in detail.  
Continuing development sometimes necessitates specification changes without notice.



**Druck Incorporated**  
Miry Brook Road  
Danbury, CT 06810  
Telephone: (203) 792-8981  
Telex: 643118  
FAX: (203) 790-9939

**Representative**



## AMPLIFIED OUTPUT PRESSURE TRANSDUCERS

Types: PDCR 130/W and PDCR 135/W  
PDCR 130/W/C and PDCR 135/W/C

**High accuracy**  
±0.1% for all ranges and pressures

**Aircraft compatible excitation**  
10-32V d.c. or ±15V a.c.

**Amplified output**  
Up to 10V

**Input/output isolation**  
PDCR 130/W series

**Integral zero and span adjustments**

**Stainless steel wetted parts**  
Absolute and gauge pressure versions

**Good thermal stability**  
±15% total resistance change from -25°F

This series of pressure transducers provide the user with a high level output signal for industrial, marine and aerospace applications, with all wetted parts manufactured from stainless steel.

Military grade electronic components are used to ensure maximum integrity. Each unit is individually calibrated and temperature compensated before shipment.

Zero and span potentiometers are provided in the rear of the transducer body and user access is via two sealed blanking plugs.

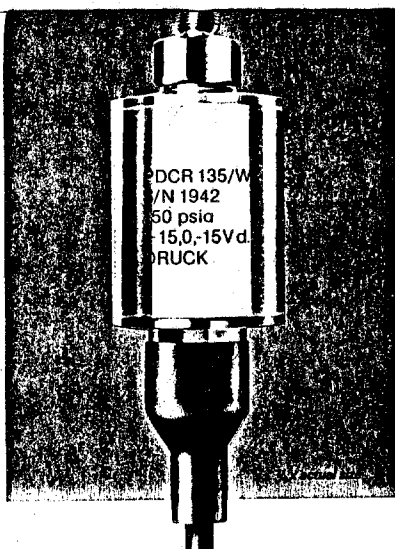
Linearizing and temperature compensation is provided within the instrument, and the rationalized outputs ensure interchangeability without system re-calibration.

During manufacture the transducers may be set to customer requirements for intermediate pressure ranges or the other pressure units.

**Operating pressure range**  
2.5psi gauge only  
5, 10, 15, 20, 30, 50, 100, 150, 200, 300, 500, 1000psi gauge or absolute 2000, 3000, 5000 and 7500 absolute  
Other pressure units may be specified e.g. ins. H<sub>2</sub>O, kPa, etc.

**Overpressure**  
The rated pressure can be exceeded by the following multiples causing negligible calibration change:  
10 X for 2.5psi range  
6 X for 5psi range  
4 X for 10psi to 200psi ranges  
3 X 200psi to 500psi ranges  
2 X 1000psi to 7500psi ranges

**Pressure media**  
Fluids compatible with 316 stainless steel



**Transduction principle**  
Integrated silicon strain gauge bridge.

**Supply voltage. PDCR 135 series**  
+15, 0, -15 Volts d.c.  
+15 Volts (±0.5 Volts) 1mA nominal  
-15 Volts (±0.5 Volts) 6mA nominal  
These currents are quoted for zero output current.  
+12, 0, -12 Volts d.c. available.

**Supply sensitivity. 0.02% F.S.O./Volt**

**Supply voltage. PDCR 130 series**  
10-32V d.c. @ 20mA isolated from output.

**Supply sensitivity. 0.005% F.S.O./Volt**  
Polarity reversal protected.

**Output voltage (isolated on PDCR 130 series)**  
±2.5V maximum for 2.5psi range  
±10V maximum for 5psi range and above

**Output current**  
PDCR 130 series: 2mA maximum. PDCR 135 series: 6mA maximum.

**Combined non-linearity and hysteresis**  
±0.1% B.S.L. for all ranges.  
±0.05% B.S.L. available for ranges up to 300psi.

**Zero offset and span setting**  
Integral trim potentiometers giving total adjustment of nominally 10% F.S.O. available on most models.

**Operating temperature range**  
-40° to +175°F (-40° to +80°C) for PDCR 130/W and PDCR 135/W  
-40° to +250°F (-40° to +125°C) for PDCR 130/W/C and PDCR 135/W/C

*This temperature range can be extended.*

PDCR 130/W & PDCR 135/W

**Temperature effects**  
±0.5% total error band 32° to 122°F (0° to 50°C)  
±1.5% total error band -5° to +175°F (-20° to +80°C)  
2.5psi range, ±0.5% total error band 50° to 105°F (10° to 40°C)

*For special applications it is possible to give improved temperature compensation over a wider range.*

**Natural Frequency (mechanical)**  
10.5kHz for 5psi range increasing to 210kHz for 500psi range

**Amplifier band width — 3dB at 2kHz nominal**

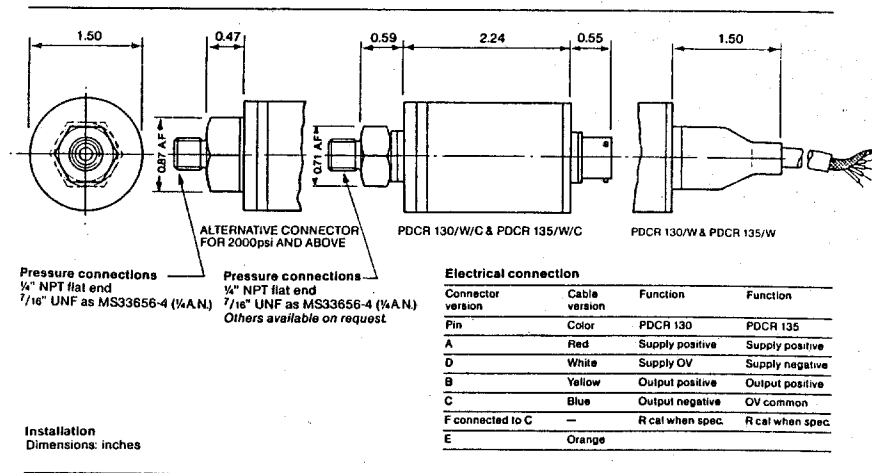
**Acceleration sensitivity**  
0.044% F.S.O./g for 5psi range decreasing to 0.005% F.S.O./g for 500psi range.

**Mechanical shock**  
1000g for 1ms in each of three mutually perpendicular axes will not affect calibration.

**Weight. 8.5 ozs. nominal**

**Electrical connection. PDCR 130/W and PDCR 135/W**  
3 feet integral vented cable standard  
Longer lengths available on request.

**Electrical connection. PDCR 130/W/C and PDCR 135/W/C**  
6 pin Bayonet fixed plug tested to MIL-C-26482 or DEF 5325 shell size 10. Free mating socket not supplied.  
Mating electrical socket Amphenol type 62GB-16F10-6S available on request.



**Druck Incorporated**  
Miry Brook Road  
Danbury, CT 06810  
Telephone: (203) 792-8981  
Telex: 643118  
FAX: (203) 790-9939

**Representative:**

PDCR 130/W & PDCR 135/W

**Options available**  
Internal shunt calibration facility.  
An extra electrical connection is provided on the transducer and if the voltage applied (referenced to the signal 0 Volt) is less than 0.8V (or open-circuit) the shunt cal will not operate, and if greater than 2.4V the output will change in a positive direction by a percentage specified during manufacture (up to the maximum output available).  
Please refer to manufacturer for other shunt cal requirements.  
General purpose gauge transducer PDCR 135 and PDCR 130 (separate data sheet).  
Differential transducer PDCR 130/WL and PDCR 135/WL (separate data sheet).  
Submersible transducer: contact manufacturer.  
Flush mounting transducer: contact manufacturer.

**Ordering information**  
Please state the following:-

- (1) Type number
  - (2) Pressure range
  - (3) Gauge, sealed gauge or absolute
  - (4) Temperature range
  - (5) Pressure connection
  - (6) Pressure media
  - (7) Supply voltage
  - (8) Output voltage
  - (9) Mating electrical socket (if required)
- For non-standard requirements please specify in detail.  
Continuing developments sometimes necessitates specification changes without notice.

MINIATURE  
UNIVERSAL VOLTAGE MODE  
**HI-FREQUENCY PRESSURE  
TRANSDUCER** w/built-in amplifier  
Series 113A20

**PCB**  
PIEZOTRONICS



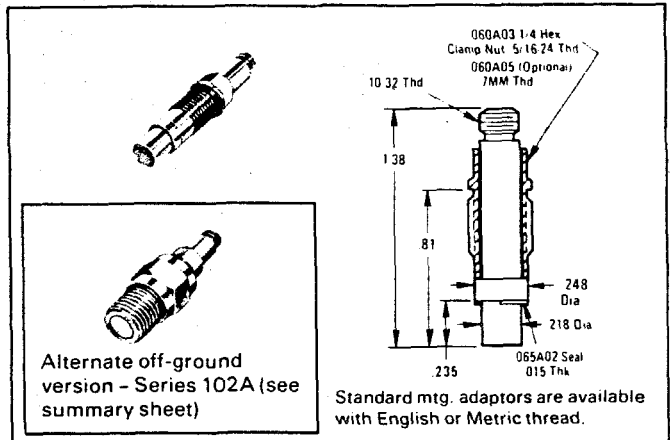
- acceleration-compensated ultra-rigid quartz element
- frequency-tailored ~ non-resonant one microsecond response
- high level (5V), low-impedance (100 ohm) analog output
- low strain and transverse motion sensitivity
- floating clamp nut with metric or American thread
- flush welded, flat diaphragm
- improved, interchangeable quartz minigage

For shock wave, blast, explosion, combustion, compression, actuation, pulsation, cavitation, ultrasonic, aerodynamic, hydraulic, fluidic and other such pressure measurements.

Transducer 113A20 consists specifically of Models 113A21, 113A22, 113A23 and 113A24. Each model is similar in performance; essentially only the full scale range and discharge time constant are different. Performance features include frequency tailoring, which minimizes resonant frequency amplitude when the transducer is subjected to extremely fast step-pressure inputs. This tailoring results in a clean, accurate output signal. The built-in electronics convert the pressure input to a clean, high resolution output which is virtually insensitive to cable length. Standard mounting adaptors simplify installation and extend versatility of the transducer.

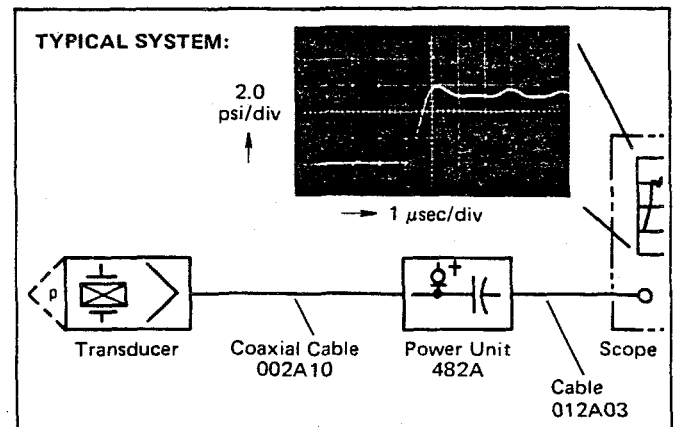
Shock tube results show these frequency-tailored transducers to be almost completely free of ringing and other internal resonance effects that can distort the signal. The rigid structure of these sophisticated instruments contains a compression mode quartz element with an integral compensating accelerometer to reduce vibration sensitivity and suppress resonance effects. Nearly non-resonant behavior is primarily achieved by meticulously matching the resonant frequency as well as the acceleration sensitivity of the compensating element to that of the pressure sensing element. A minimum number of quartz plates imparts structural integrity.

Miniature quartz transducers install flush or recessed in existing or new minigage ports directly in the test object or in a variety of threaded mounting adaptors, which are also available as off-ground factory sealed assemblies. When connected to a PCB power unit, these self amplifying transducers generate a high level, low impedance analog output signal compatible with most readout instruments. The simple power unit circuit powers the transducer over the signal lead (coaxial or 2-wire), eliminates output bias and indicates normal or faulty operation. Signal quality is almost independent of cable length, condition and motion.



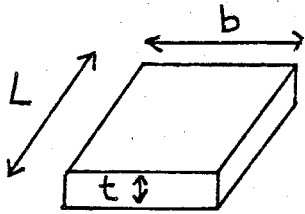
SPECIFICATIONS: Model No.		113A21
Range (1 volt output)	psi	50
Range (5 volt output)	psi	250
Useful Overrange (10 volt output)	psi	500
Maximum Pressure	psi	3000
Resolution (Noise 200 $\mu$ V p-p)	psi	0.01
Sensitivity	mV/psi	20
Resonant Frequency	kHz	500
Rise Time	$\mu$ s	1
Discharge Time Constant	s	1
Low Frequency Response (-5%)	Hz	0.5
Linearity (zero based BSL)	%	1
Polarity		Positive
Output Impedance	ohm	100
Output Bias (nominal)	volt	11
Acceleration Sensitivity	psi/g	0.002
Temperature Coefficient	%/ $^{\circ}$ F	0.03
Temperature Range	$^{\circ}$ F	-100 to +275
Maximum Flash Temperature	$^{\circ}$ F	3000
Vibration; Shock	g's peak	2000; 20 000
Case; Diaphragm		17-4PH; INVAR
Weight	gm	6
Excitation/Constant Current	VDC/mA	+18 to 28/2 to 20
<b>Model No. (other 5V Ranges)</b>		
1000 psi, 100 sec TC	5 mV/psi	113A24
5000 psi, 500 sec TC	1 mV/psi	113A22
10 000 psi, 1 000 sec TC	0.5 mV/psi	113A23

Note: Special case diaphragm materials are available. For metric (M7 x .75) thread, add prefix 'M' before model no., e.g. M113A21. For hermetic sealing use prefix 'H', e.g. H113A21. For both metric and hermetic use prefix 'HM', e.g. HM113A21.



## TEST SECTION STRESS ANALYSIS

Highest stress at high speed stream settling chamber.  
Model as a flat plate of uniform thickness with clamped boundary conditions and uniform loading:



Data:  $t = 2.75$  in (min. thickness @ screen cutouts)

$b \approx 9.0$  in (between O-rings)

$L = 36$  in (inlet to throat)

Roark & Young (1982) give the formula:

$$\sigma_{\max} = \frac{\beta_1 q b^2}{t^2}$$

where  $q =$  uniform pressure loading  $= P_s$   
 $\beta_1 \approx 0.5$  for  $L/b = 4$

$\sigma_{\max} = 9,000$  psi (6061-T6 Al,  
safety factor = 4)

$$\therefore q = P_s = \frac{(9000)(2.75)^2}{(0.5)(9.0)^2} \Rightarrow \boxed{P_s = 1680 \text{ psi}}$$

This is undoubtedly conservative since the thickness is 3.5 in at the edges of the plate, where the maximum stress occurs.

## Appendix E: Exhaust System

This appendix describes the exhaust system in greater detail. The information provided consists of:

- Data sheet describing the high pressure shower nozzles.
- Data sheet describing the catch bag material.
- Data sheet describing the high pressure shower pump.
- Drawing of the catch bag support structure.

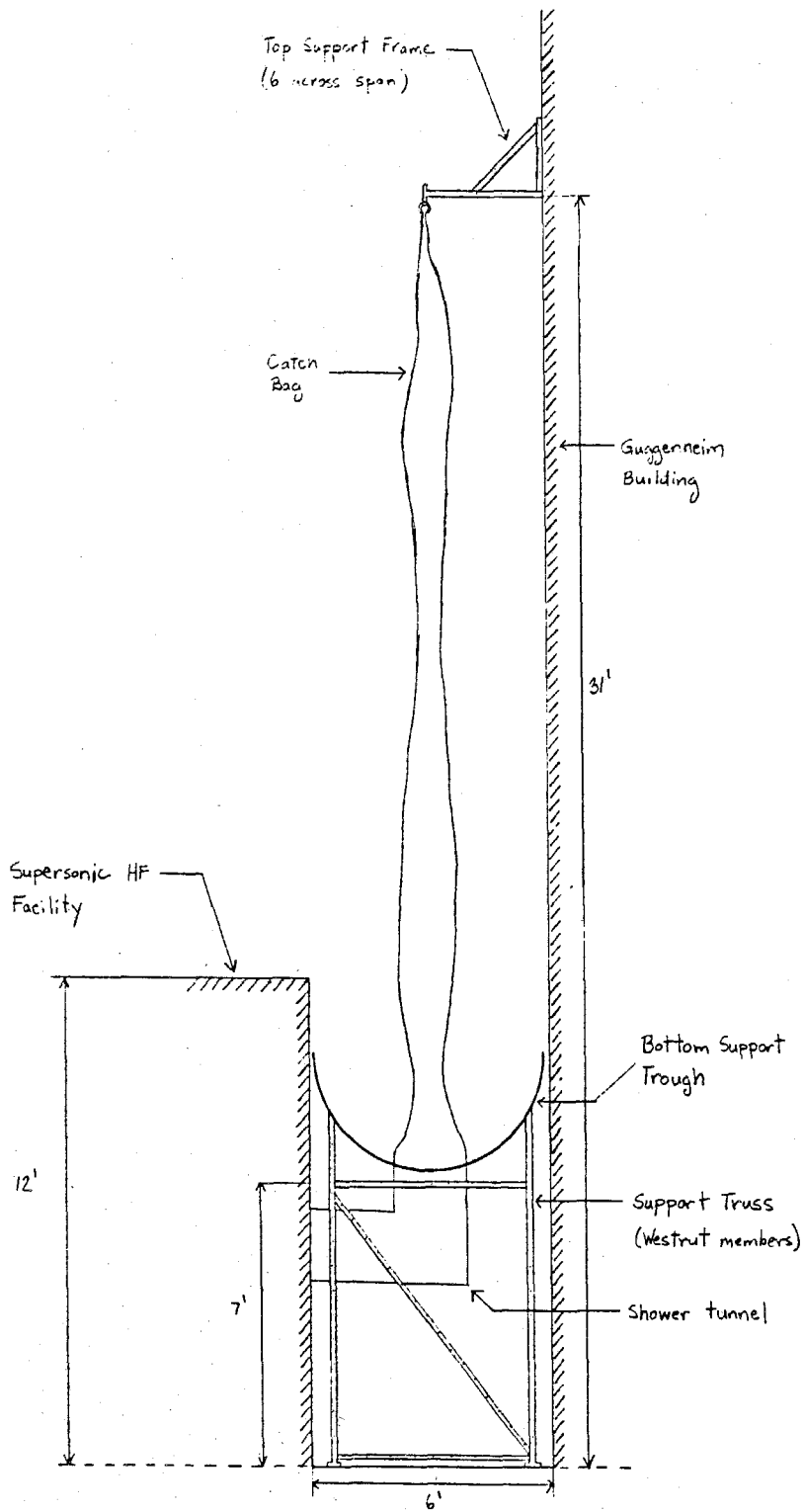
# CATCH BAG GEOMETRY

0 1 1/2 3 ft

Scale: 1/30

Drawn by: Jeff Hall

Dated: 08/27/89



# FogJet

## LARGE CAPACITY/WIDE ANGLE SMALL DROPLET SIZE/MULTIPLE ORIFICE/FULL CONE

### 7N

atomizing spray caps  
1" NPT (F)



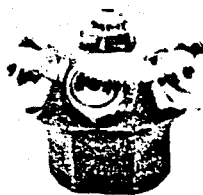
### DESIGN FEATURES

The 7N series FogJet nozzle produces a shower-like full cone spray pattern of very fine droplets.

The nozzle assembly consists of a nozzle body and seven removable atomizing spray caps. Each cap has an internal vane which is easily removed for cleaning or replacement.

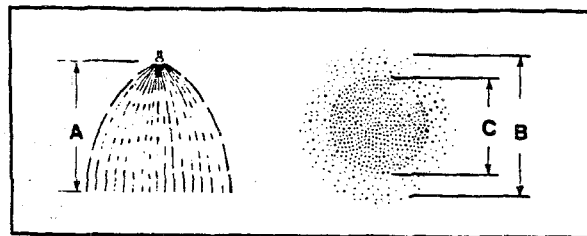
### 7G

FullJet spray caps  
3/4"-1 1/2" NPT (F)



The 7G series FogJet nozzle produces a shower-like full cone spray pattern. The 7G series nozzle provides large flow capacities with relatively small droplets.

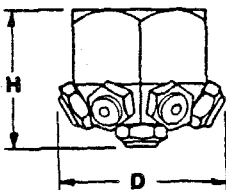
The nozzle assembly consists of a nozzle body and seven removable FullJet spray caps. Each cap has an internal vane which is easily removed and replaced.



### DIMENSIONS & WEIGHTS

Based on largest/heaviest version of each type

Nozzle No.	Pipe Conn. NPT	H Inches	D Inches	Net Weight
3/4-7G1 thru 3/4-7G3	3/4	1 25/32	2 1/8	12 oz.
3/4-7G5	3/4	1 13/16	2 1/8	12 oz.
1-7G10 and 1-7G12.5	1	2 3/16	2 11/16	1 1/2 lbs.
1-7G25 thru 1-7G40	1	3 3/16	4 1/8	3 1/2 lbs.
1-1/2-7G25 thru 1-1/2-7G45	1 1/2	3	4	3 3/4 lbs.
1-1/2-7G50	1 1/2	3 3/16	4 1/4	3 1/2 lbs.
All 1-7N	1	2 1/2	2 1/2	1 1/2 lbs.



### ORDERING INFORMATION

STANDARD  
SPRAY NOZZLE

1-1/2 - 7G - SS 30

Inlet Connection Pipe Size    Nozzle Type    Material Code    Capacity Size

EX: 1 1/2-7G-SS30

Model 7G FogJet spray nozzle with 1 1/2" NPT (F) inlet connection, removable spray caps, all stainless steel construction, and 30 capacity size performance specifications.

Material Code

no material code = Brass

SS = 303 Stainless Steel

309SS = 309 Stainless Steel

316SS = 316 Stainless Steel

Inlet NPT	Nozzle Type	Capacity Size	SPRAY PATTERN			CAPACITY (gallons per minute)							
			A Feet	B Feet	C Feet	20 psi	40 psi	60 psi	80 psi	100 psi	125 psi	150 psi	
1	7N	.60	3"	3 1/2"	1 1/2"					.11	.12	.14	
		1	3"	4"	2"		.12	.14	.16	.18	.21	.23	
		1.5	3"	4 1/2"	2 1/2"		.17	.21	.25	.28	.31	.34	
		2	3"	4 1/2"	2 1/2"		.23	.29	.33	.37	.41	.45	
		3	3"	5 1/2"	3 1/2"	.25	.35	.43	.50	.55	.62	.68	
		4	3"	5 1/2"	3 1/2"	.33	.47	.57	.66	.74	.83	.90	
		6	3"	6"	4"	.50	.70	.86	.98	1.1	1.2	1.4	
		8	3"	6"	4"	.66	.93	1.1	1.3	1.5	1.7	1.8	
		10	3"	7"	4 1/2"	.83	1.2	1.4	1.7	1.8	2.1	2.3	
		12	3"	8"	4 1/2"	1.0	1.4	1.7	2.0	2.2	2.5	2.7	
		14	3"	8"	4 1/2"	1.2	1.6	2.0	2.3	2.6	2.9	3.2	
		16	3 8 7 8 1/2	5 5 1/2	1.3	1.9	2.3	2.6	3.0	3.3	3.6		
		18	3 8 7 9	5 6	1.5	2.1	2.6	3.0	3.3	3.7	4.1		
		22	3 9 1/2 7 11	5 5 1/2 7 7	1.8	2.6	3.2	3.6	4.1	4.5	5.0		
26	3 10 7 12	6 8	2.1	3.0	3.7	4.3	4.8	5.4	5.9				
3/4	7G	1	3 5 8 6 1/2 11 7 1/2	3 3 1/4 4 4 1/4 5 4 3/4	.98	1.3	1.6	1.8	2.1	2.3	2.5		
		1.5	3 5 8 9 11 10 1/2	5 5 1/2 6 6 1/2 7 7 1/2	1.5	2.0	2.4	2.8	3.1	3.4	3.7		
		3	3 8 1/2 5 10 8 11	5 5 1/2 6 6 1/2 7 7 1/2	2.9	4.0	4.8	5.5	6.2	6.8	7.4		
		5	3 9 1/2 5 11 8 12 11 12 1/2	6 6 1/4 7 7 7 3/4 8	4.8	6.7	8.1	9.2	10.3	11.3	12.4		
1		10	3 11 5 12 1/2 8 13 1/2 11 14	9 9 1/2 10 10 11 11 12 12	9.8	13.5	16.4	18.9	21.0	23	25		
		12.5	3 12 5 13 1/2 8 14 11 14 1/2	10 10 11 11 12 12 12 1/2	12	17	20	23	25	28	30		
1 or 1-1/2		25	3 13 3/4 5 16 8 17 11 17 1/2	9 9 10 10 1/2 11 11 11 1/2	24	34	41	47	52	57	62		
		30	3 13 3/4 5 16 8 17 11 17 1/2	9 9 10 10 1/2 11 11 11 1/2	29	40	48	55	62	68	74		
		32	3 13 3/4 5 16 8 17 11 17 1/2	9 9 10 10 1/2 11 11 11 1/2	31	43	52	59	66	74	79		
		40	3 13 3/4 5 16 8 17 11 17 1/2	9 9 10 10 1/2 11 11 11 1/2	39	53	64	74	83	92	100		
1-1/2		45	3 14 5 16 1/2 8 17 1/2 11 18	9 9 1/2 11 11 12 12 12 1/2	44	60	72	82	91	100	110		
		50	3 14 1/2 5 17 8 18 11 19	10 10 1/2 12 12 13 13 1/2 14	48	67	81	92	103	113	124		

\*And Up

D1

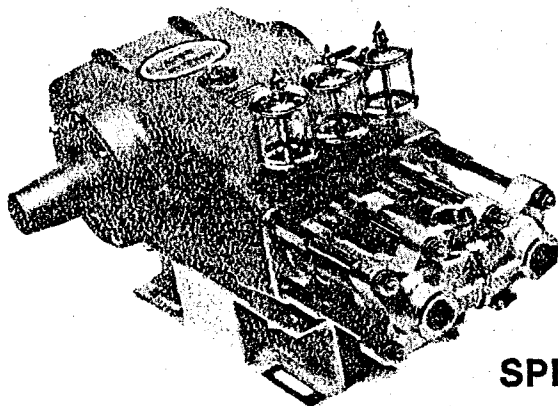


FINE SPRAY/FULL CONE



**Kepner Plastics Fabricators, Inc.**  
**3131 Lomita Blvd. (213) 325-3162**  
**Torrance, California 90505**

	KEPTEX APR3018B	
	Std.	Metric
Base — Type Fabric — Weight	Polyester 6.5 oz/sq yd	Polyester 225 g/m <sup>2</sup>
Finished Coated Weight ASTM D-751	30 ± 2 oz/sq yd	1020 ± 70 g/m <sup>2</sup>
Tongue Tear ASTM D-751 Tongue Method (8" x 8" sample size)	125/125 lbs.	57/57 kg
Trapezoid Tear ASTM D-2263	35/35 lbs.	16/16 kg
Grab Tensile ASTM D-751 Grab Method	475/425 lbs.	216/193 kg
Strip Tensile ASTM D-751 Cut Strip Method	400/350 lbs.	182/159 kg
Adhesion (min.) ASTM D-751 Adhesion Para. b — dielectric seam	10 lbs/in	1.8 kg/cm
Hydrostatic Resistance ASTM D-751 METHOD A Procedure 1	500 psi	35 kg/cm <sup>2</sup>
Puncture Resistance FTMS 101B Method 2031	350 lbs.	159 kg
Dead Load Room Temperature: 160°F/71°C:	2" seam 210 lbs. 105 lbs.	5.8 cm seam 95 kg 47.5 kg
Cold Crack ASTM D-2136 1/8" Mandrel 4 hours	Pass @ -30°F	Pass @ -35°C
Flame Resistance Method 5910 MFR	Not Consumed in 2 Minutes	



## Model 6020 and 6040 OPERATING INSTRUCTIONS

**CAUTION:** CAT PUMPS are positive displacement pumps. Therefore, a properly designed pressure relief mechanism **MUST** be installed in the discharge piping. Failure to install such relief mechanism could result in personal injury or damage to the pump or system. Cat Pumps Corporation does not assume any liability or responsibility for the operation of a customer's high pressure system.

### SPECIFICATIONS

	Model 6020		Model 6040	
	U.S. Measure	Metric Measure	U.S. Measure	Metric Measure
Volume.....	60 GPM	(227 L/M)	40 GPM	(151 L/M)
Discharge Pressure .....	1000 PSI	(69 BAR)	1500 PSI	(104 BAR)
Maximum Inlet Pressure .....	-8.5 to +40 PSI	(-0.6 to +2.8 BAR)	-8.5 to +40 PSI	(-0.6 to +2.8 BAR)
RPM.....	500 RPM	(500 RPM)	500 RPM	(500 RPM)
Bore.....	2.205"	(56mm)	1.81"	(46mm)
Stroke.....	2.461"	(62.5mm)	2.461"	(62.5mm)
Crankcase Capacity.....	10 QTS.	(9.46L)	10 QTS.	(9.46L)
Maximum Fluid Temperature .....	160°F	(71°C)	160°F	(71°C)
Inlet Ports (1).....	2" NPT	(2" NPT)	2" NPT	(2" NPT)
Discharge Ports (2).....	1 1/4" NPT	(1 1/4" NPT)	(1 1/4" NPT)	
Pulley Mounting.....	Either Side	(Either Side)	Either Side	(Either Side)
Shaft Diameter.....	1.772"	(45mm)	1.772"	(45mm)
Weight.....	235 lbs.	(110 kg)	235 lbs.	(110 kg)
Dimensions .....	31.4x24.0x17.1"	(797x610x434mm)	31.4x24.0x17.1"	(797x610x434mm)

### CAT PUMP WARRANTY

This Cat Pump ("product") is warranted by the manufacturer to be free from defects in workmanship and material for one year from date of manufacturer's Shipment. This warranty is limited to repairing or replacing products which manufacturer's investigation shows were defective at the time of shipment by the manufacturer. All products subject to this warranty shall be returned F.O.B. Cat Pumps Corp., Minneapolis, Minnesota 55430, U.S.A. for examination, repair or replacement.

The express warranty set forth herein is in lieu of all other warranties, express or implied, including without limitation any warranties of merchantability or fitness for a particular purpose and all such warranties are hereby disclaimed and excluded by the manufacturer. Repair or replacement of defective products as provided above is the sole and exclusive remedy provided hereunder and the manufacturer shall not be liable for any further loss, damages or expenses, including incidental or consequential damages, directly or indirectly arising from the sale or use of this product.

This warranty is subject to the following warranty conditions:

### IMPORTANT CONDITIONS

**LUBRICATION** — Fill crankcase to dot on oil dipstick per specifications with Cat Pump Oil or equivalent SAE 40 weight hydraulic oil with anti-wear and rust inhibitor additives. Change initial fill after 50 hour run-in period. Change oil every 3 months or at 500 hour intervals thereafter.

**OILERS:** Prior to initial operation fill the three oilers with Cat Pump oil. With the oiler shut-off lever in a vertical position, screw the dome down to seat the needle valve tightly. (The shut-off lever becomes loose.) Then back the needle off the valve seat slightly (approximately 1/8 turn) and tighten the lock nut. Prior to initial operation saturate wicks. Then run pump 1-2 hours with 3-4 drops per hour from each oiler; thereafter, 1 drop per hour per oiler. Flipping the shut-off lever to the horizontal position shuts off the oil flow.

**GOOD LUBRICATION IS THE EASIEST, MOST EFFICIENT AND LEAST EXPENSIVE OF PREVENTATIVE MAINTENANCE.**

**RPM and PRESSURE** — Pump operation must be within RPM and pressure specifications. Pressure relief valve must be installed.

**DO NOT PUMP ACIDS OR ABRASIVE FLUIDS** with this unit. Consult Cat Pumps for additional information on questionable fluids.

**FREEZING CONDITIONS** — Pump must be protected from freezing conditions.

**USE OF OTHER THAN CAT PUMP PARTS OR THEIR EQUIVALENT VOIDS THE WARRANTY**

Products described hereon are covered by one or more of the following U.S. patents: 3558244, 3652188, 3809508, 3920356, and 3930756.



1600 FREEWAY BOULEVARD N. MINNEAPOLIS, MN 55430  
Phone (612) 566-1212 • Telex 29-0276

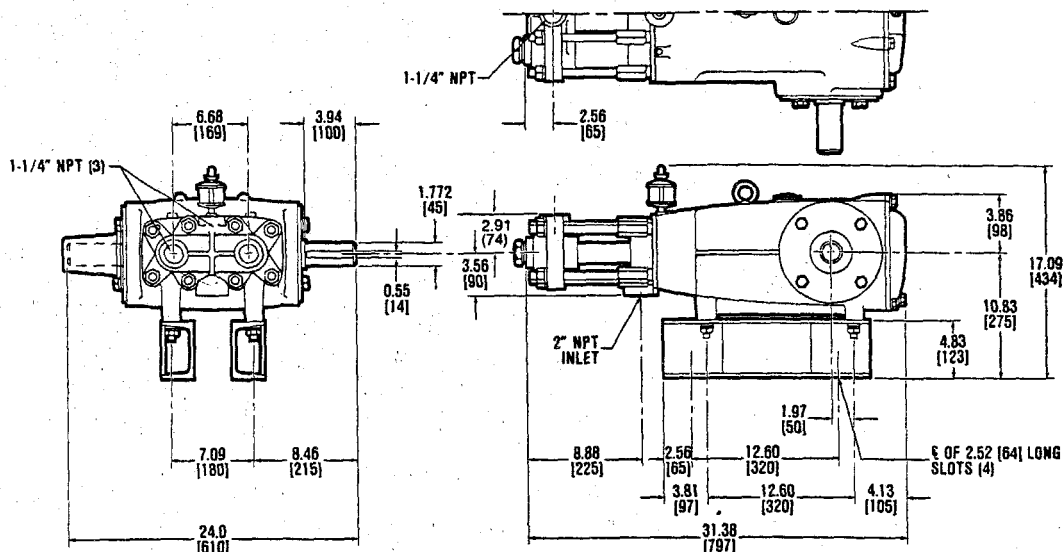
N.V. CAT PUMPS INTERNATIONAL S.A.  
Harmoniestraat 29  
B-2000 Antwerp, Belgium

CAT PUMPS — A. G.  
Loretöhöhe 5  
CH-6300, ZUG, Switzerland

CAT PUMPS DEUTSCHLAND GmbH  
Rostocker Strasse 9  
6200 Wiesbaden-Bierstadt  
West Germany

CAT PUMPS (U.K.) LTD.  
17A Kings Road, Fleet  
Hampshire GU13 9AA  
England

Distributed By:



## IMPORTANT DRIVE INFORMATION

Model 6020 Horsepower Requirements						Pump Pulley Consult Pulley Mfr.	
Flow		Pressure				RPM	Motor Pulley O.D.
		700 PSI	800 PSI	900 PSI	1000 PSI		
GPM	L/M	48 BAR	55 BAR	62 BAR	69 BAR		
60	277	28.9	33.0	37.1	43.8	500	Consult
50	189	24.0	27.5	30.9	34.3	417	Pulley
40	151	19.2	22.0	24.7	27.5	333	Mfr.
30	114	14.4	16.5	18.6	20.6	250	

Model 6040 Horsepower Requirements						Pump Pulley Consult Pulley Mfr.	
Flow		Pressure				RPM	Motor Pulley O.D.
		1100 PSI	1200 PSI	1400 PSI	1500 PSI		
GPM	L/M	76 BAR	83 BAR	97 BAR	104 BAR		
40	151	32.1	33.0	40.8	43.8	500	Consult
35	133	28.1	28.9	35.7	36.1	478	Pulley
30	114	24.1	24.7	30.6	30.9	375	Mfr.
25	95	20.1	20.6	25.5	25.8	318	

Pump speed and pump output in gallons per minute as tabulated is based upon a 1725 RPM drive motor. Select motor pulley size to provide GPM of the approximate pump output desired.

Pump RPM and GPM output are approximate values due to variations in pulleys, belts and motors between manufacturers and a

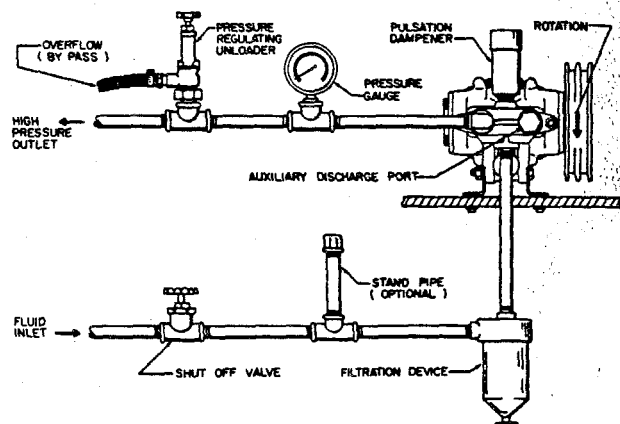
+ - 5% pump output tolerance.

Horsepower figures shown are brake horsepower figures. For gas engines requirements, follow engine manufacturer's recommendations. In general, use a gas engine with approximately double the electric motor horsepower.

## TYPICAL INSTALLATION

The illustration at the right shows the basic elements for the proper installation of the high-pressure pump. Each component offers potential problems that too often are ascribed to a perfectly functioning pump. A clogged strainer, a partially closed shut-off valve or a faulty pressure gauge or pressure regulating unloader may be the source of trouble.

Proper system installation, routine lubrication and monitoring of components are your best guarantees of optimum pump performance. These precautions will eliminate most problems, minimize corrective maintenance, and give many, many added hours of trouble free operation. Cat Pumps Corporation does not assume any liability or responsibility for the operation of a customer's high pressure system.



## Appendix F: Performance Calculations

This appendix presents some calculations which provide estimates for the performance of the facility. The information provided consists of:

- Calculation of shear layer thickness  $\delta$ , and Reynold's numbers  $Re_\delta$  and  $Re_x$ .
- Analysis of the  $H_2/NO$  Reactant Tank blowdown and main regulator open loop control.
- Graphs showing  $H_2/NO$  Reactant Tank starting pressure as a function of free stream Mach number, gas and temperature.

## CALCULATION OF $\delta$ , $Re_\delta$ , $Re_x$

For subsonic, gas-phase shear layers of roughly uniform density,

$$\frac{\delta}{x} \approx 0.17 \quad (1) \quad [\text{See Dimotakis (1989)}]$$

The results of Papamoschou (1986, 1988, 1989) et al suggest that supersonic shear layers grow at only 20% of subsonic shear layers. Therefore,

$$\frac{\delta}{x} \approx 0.034 \quad (2) \quad \text{for } M_c \geq 0.5$$

This facility has

$$x \approx 24 \text{ inches} \Rightarrow \dots \delta \approx 0.82 \text{ in} \quad (3)$$

Define:

$$Re_\delta = \frac{\delta \Delta U}{\nu}$$

$$Re_x = \frac{x \Delta U}{\nu}$$

or, given eq. (2)

$$Re_\delta = 0.034 Re_x \quad (4) \quad \text{for supersonic shear layers}$$

To compute  $\nu$  for the supersonic stream, we will assume

$$\frac{\mu}{\mu_0} \approx \left( \frac{T}{T_0} \right)^{0.7} \Rightarrow \frac{\nu}{\nu_0} = \left( \frac{T}{T_0} \right)^{1.7} \quad (5)$$

for  $P = P_0 = 1 \text{ atm}$ .

Sample Calculation for  $M_1 = 3.2$  in  $N_2$ ,  $M_2 \approx 0$ :

$$\nu_0 = 1.5 \times 10^{-5} \text{ m}^2/\text{s}$$

$$a_0 = 353 \text{ m/s}$$

$$T_0 = 300 \text{ K}$$

$$u_1 = M_1 a_1 = \frac{M_1 a_0}{\sqrt{1 + \frac{\gamma-1}{2} M_1^2}}$$

$$\gamma = 1.4$$

$$\therefore u_1 = 647 \text{ m/s}$$

$$\text{But } \Delta u = u_1 \quad \therefore \Delta u = 647 \text{ m/s}$$

Next,

$$\frac{T}{T_0} = \left(\frac{a}{a_0}\right)^2 \Rightarrow \frac{T}{T_0} = 0.328$$

Therefore,

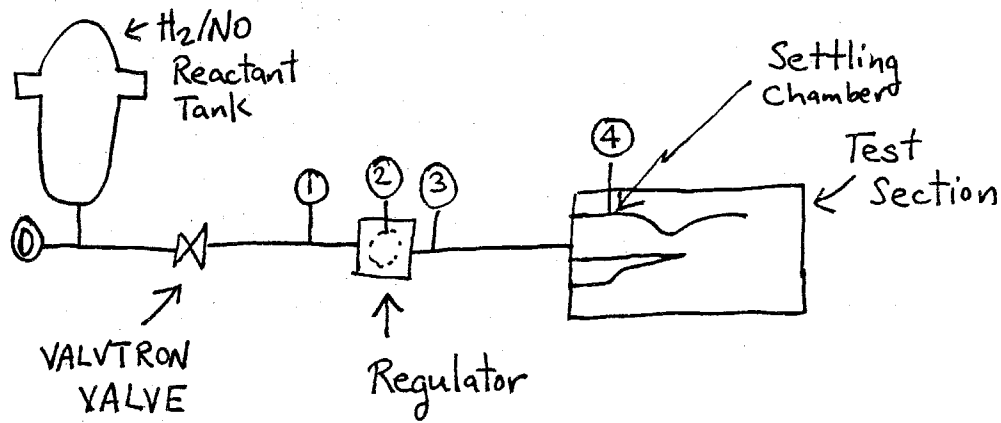
$$\nu = 2.26 \times 10^{-6} \text{ m}^2/\text{s}$$

$$\therefore Re_x = \frac{(647)(0.61)}{2.26 \times 10^{-6}} = 1.75 \times 10^8$$

$$\text{where } x = 0.61 \text{ m} \\ (= 24 \text{ in})$$

$$\therefore Re_s = 0.034 Re_x \Rightarrow Re_s = 5.9 \times 10^6$$

# H<sub>2</sub>/NO Reactant Tank Blowdown and Regulator Open-Loop Control



Blowdown Analysis:

$$\text{Mass in tank} = M_0 = \rho_0 V_0 \quad (1) \quad \rho_0 = \text{density}, V_0 = \text{volume}$$

$$\text{Ideal gas law for tank} \Rightarrow P_0 = \rho_0 R T_0 \quad (2) \quad \begin{array}{l} T_0 = \text{temperature} \\ P_0 = \text{pressure} \\ R = \text{gas constant} \end{array}$$

Combine (1) and (2) :

$$P_0 = \frac{M_0 R T_0}{V_0} \quad (3)$$

Now,  $V_0 = \text{constant}$ ,  $T_0 \approx \text{constant}$  due to Aluminum packing.  
Therefore,

$$\frac{dP_0}{dt} = \frac{R T_0}{V_0} \frac{dM_0}{dt} \quad (4)$$

For constant test conditions,  $\frac{dM_0}{dt} = \text{constant}$

Therefore, we expect  $\frac{dP_0}{dt} = \text{constant}$  during the run.

Now, the mass flux is uniquely specified by the conditions of the experiment: free stream Mach number, nozzle exit area, Stagnation pressure and temperature. Hence, we can assume  $\dot{m}_4$  is known for steady flow and that

$$\dot{m}_0 = \dot{m}_4 \quad (5) \quad \text{from continuity.}$$

Therefore,  $\frac{dP_0}{dt}$  is also known, once steady flow is established.

### Regulator Analysis:

If we operate the regulator such that flow through it is choked, then

$$\dot{m}_2 = A_2 P_{2t} \sqrt{\frac{\gamma}{RT_{2t}}} F(\gamma) \quad (6) \quad \text{where } F(\gamma) = \left(\frac{\gamma+1}{2}\right)^{-\frac{1}{2} \frac{\gamma+1}{\gamma-1}}$$

$A_2$  = flow area,  $P_{2t}$  = total upstream pressure,  $T_{2t}$  = total temperature.

The regulation process is very nearly adiabatic; therefore,

$$\dot{m}_2 \sim A_2 P_{2t} \quad (7)$$

For steady flow,

$$\dot{m}_2 \simeq \dot{m}_0 \simeq \dot{m}_4 \quad \text{and} \quad P_{2t} \simeq P_0$$

Hence,

$$A_2 \sim \frac{\dot{m}_0}{P_0} \quad (8)$$

Since  $\dot{m}_0$  is specified, and  $P_0$  is given from (4), we can predict  $A_2(t)$  such that the flow is steady.

This is the basis of the open loop control scheme.



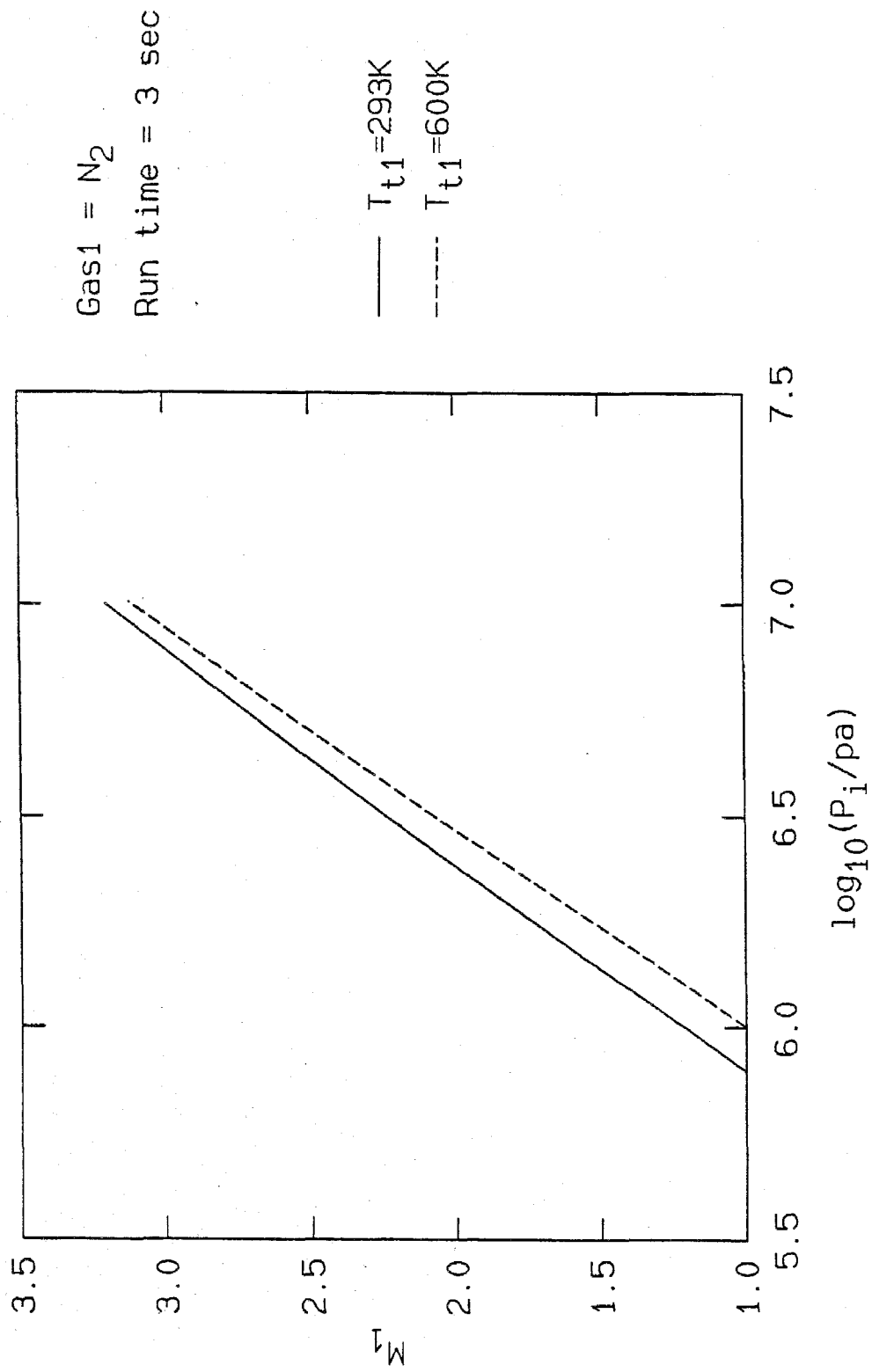


Figure 14: Free Stream Mach Number vs Initial Tank Pressure

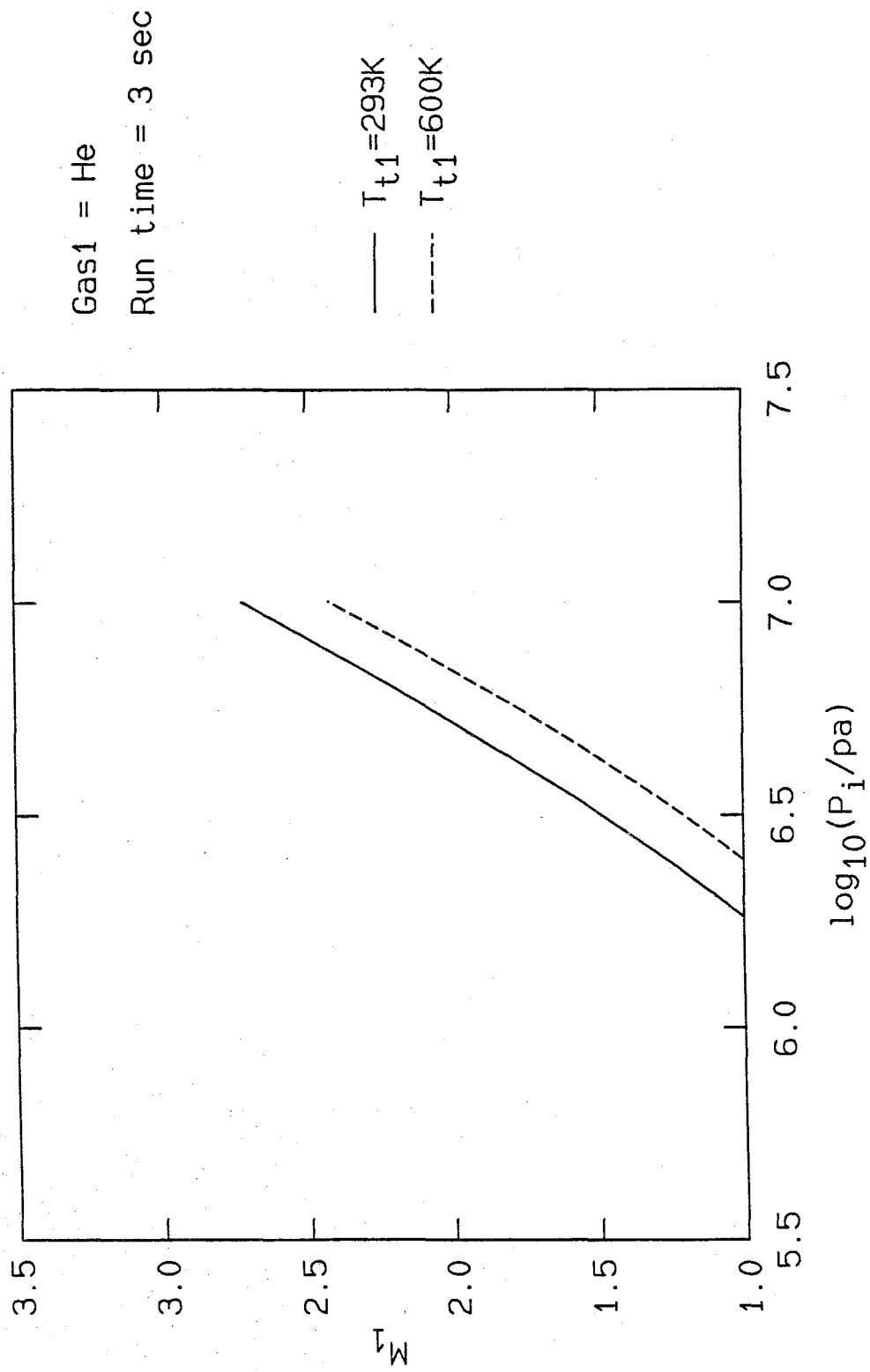


Figure 16: Free Stream Mach Number vs Initial Tank Pressure